A BALLOON-BORNE TELEMETERING DEVICE FOR THE
MEASUREMENT OF RAINDROP-SIZE DISTRIBUTIONS
IN THE VERTICAL

by

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## ABSTRACT

**A BALLOON-BORNE TELEMETERING DEVICE FOR THE MEASUREMENT OF RAINDROP-SIZE DISTRIBUTIONS IN THE VERTICAL**

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Submitted to the Department of Meteorology on April 7, 1965 in partial fulfillment of the requirement for the degree of Master of Science in Meteorology.

An instrument has been designed, constructed, and tested for the purpose of measuring raindrop sizes by means of measuring their terminal velocities. The device obtains the vertical velocity of each raindrop by measuring the time that it takes the drop to descend through a given vertical displacement bounded by two light-photocell circuits. The system will sense reliably droplets as small as 0.5 millimeters in diameter.

Throughout the design and construction of this instrument, large emphasis has been placed on minimizing weight and power requirements in order to allow the use of standard meteorological balloons as ascent vehicles. Also, emphasis has been placed on minimizing the cost per flight since the instrument is non-recoverable and it would be desirable to make several ascents during different stages of each storm.

Sample size limitations and amplitude modulated static have necessitated cancellation of the balloon-borne model of the conceived instrument. In its place a surface model has been automated, refined, and ruggedized to the extent that drop-size measurements could be initiated by the rain itself. Times corresponding to the terminal velocities and, hence, to the diameters of the drops are printed digitally on a continuous paper record up to a maximum rate of five per second. Since rainfall rates cover such a wide spectrum, adjustment of the sample area facilitates maintaining the sampling rate at close to its maximum.

The system is advantageous in that it requires no calibration to measure the vertical components of the fall velocities of the raindrops. Possible raindrop horizontal velocity components do not reduce the accuracy of the results since the raindrops are embedded in the horizontal flow and, therefore, do not meet air resistance in that direction. Thus, the instrument may be used to measure accurately raindrop sizes during all rainstorm conditions except those involving heavy local turbulence.

Thesis Supervisor: Title:

## ACKNOWLEDGEMENT

Indeed, during the course of the design, construction, and testing of this thesis project every member of the M.I.T. Weather Radar Project has contributed toward the attainment of the final goal. Although each Project member has contributed a varying degree of assistance, Greg Nealand, my Systems Engineer, has worked side by side with me for the past year to translate our mutually achieved ideas into working electronic systems. His own initiative, drive, and inventiveness have prevented many an apparent failure from derailing the project. My hat is off in appreciation and recognition of one who has never doubted the feasibility of the project and has put enough of himself into it to make it work.

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## I. GENERAL INTRODUCTION AND WEATHER RADAR JUSTIFICATION

The measurement of raindrop sizes is important for each of two reasons. Historically, as well as presently, investigators have desired to measure the distribution of raindrop sizes for their value in understanding more about precipitative processes. Most of the successful measurements have been made only at the ground and therefore have not been adequate for a complete understanding of the life histories of liquid precipitative elements because the distribution of raindrop sizes at the surface is a function not only of the sizes, the locations, and the movements of the precipitative source areas aloft; but also of the growth, evaporation, or droplet break-up that the particles experience during their descents to the surface.

It is seen, therefore, that a device which is capable of measuring drop sizes continuously while ascending through different layers of rain storms would be quite valuable in terms of the information it could provide concerning the life history of rain.

The second rationale for building such a device is concerned with the more accurate measurement of rainfall rates and, hence, total amounts of rainfall. Present-day, large-scale, rainfall rate measurements are accomplished by a synoptic raingauge network. However, this network is not fine enough to give the coverage that is necessary to yield an accurate estimate of the instantaneous distribution of rainfall rates or the total amount of rain falling on a given area. Also many of the raingauges give an areal distribution of rainfall amounts which is available only in hourly increments. Since the lifetime of some storms is on the order of an hour, these raingauge reports can give no accurate estimate of the instantaneous rainfall rate during each hour.

The only tool now in use which is capable of giving information on the three-dimensional distribution of rainfall rates on fine scales in both distance and time is weather radar. Unfortunately, even with a precisely calibrated radar, there is no one to one correspondence between the power scattered back to the radar antenna and the average rainfall rate occurring within the volume sampled by the radar. Since the receiving system measures the total power, it cannot distinguish between many small scatterers and a very few large scatterers. Studies such as the one by Gunn and East (1954) show that the radar reflectivity per unit volume is proportional to the sum of the sixth powers of the diameters of the drops. This sum shall be referred to hereafter as $\underline{Z}$.

Many researchers have investigated the relationship between $\underline{Z}$ and $\underline{R}$, the rainfall rate as computed from drop-size information. Although the actual relationship between $\underline{Z}$ and $\underline{R}$ varies from storm to storm, one empirical relationship has been given by many investigators as the overall, best fit. This relationship is that $\underline{Z}$ is 200 times the 1.6th power of $\underline{R}$.

The radar equation can be expressed in terms of an equivalent $\underline{Z}$, $\underline{Z_e}$, which is a radar reflectivity factor and has the same dimensions as $\underline{Z}$ except that $\underline{Z_e}$ is measured with the radar while $\underline{Z}$ requires measurements of the individual drops for its computation. In order to use the radar as an instrument for estimating rainfall rate some relationship must be assumed between $\underline{Z_e}$ and $\underline{R_e}$, the estimated, average rainfall rate throughout the volume of air sampled by the radar. The frequently assumed relationship, $Z_e = 200R_e^{1.6}$, has been based directly on the $\underline{Z\text{-}R}$ relationship found in drop-size measurements. However, since the assumed relationship is based on an average, it is usually somewhat in error for a particular storm. Comparisons have been made on a seasonal basis (See Section VII) between $\underline{Z_e}$, as measured by the M.I.T. ten centimeter radar, and $\underline{R_r}$, the rainfall rate as measured by a recording raingauge underneath the volume of air sampled by the radar. These indicate that $Z_e = 200R_r^{1.6}$ does not hold even in the average for each of the four seasons. This is not surprising since $\underline{R_r}$, the measured rainfall rate at one point under the sampled volume does not always correspond to the average of rainfall rates throughout the volume. Thus the use of radar as a tool for accurately measuring rainfall rates depends upon the correct determination of a relationship between $\underline{Z_e}$ and $\underline{R_e}$ for various seasons and storm situations. This relationship can never be investigated completely through a consideration of the relationship between $\underline{Z_e}$ and $\underline{R_r}$ because of the sampling volume differences between $\underline{R_r}$ and $\underline{R_e}$. Raingauge rainfall rates, $\underline{R_r}$, could approximate the average rainfall rate in the volume if many raingauges were placed beneath the sampled volume and averaged properly. However, the radar reacts directly to spherical scatterers; therefore, more concern should be directed towards measuring the distributions of drop sizes. In this way, selective, drop-size, sampling problems concerned with recording raingauges will be eliminated. If further steps are taken to insure that many, drop-size distributions are measured at different levels in many storm types, eventually a record may be obtained of the variation of $\underline{Z_e}$ with $\underline{\overline{R_d}}$, the average of rainfall rates over the sampled volume as measured by the drop-sampling technique. This type of record would facilitate the estimation of the proper relationship between $\underline{Z_e}$ and $\underline{R_e}$ for varying seasons, storm types, and possibly for the state of maturity of a given storm type.

Plans for an airborne device for measuring drop-size distributions have been described by the Weather Radar Research Project as early as their First Technical Report dated December 31, 1946.

The past year has been spent by the author in developing a system for measuring drop-size distributions which is believed to possess fewer shortcomings and greater accuracy than previously developed instruments, as well as a capability of continuous measurements which could be fed directly into a computer for the desirable statistical manipulations.

## II. HISTORY OF DROP-SIZE MEASUREMENTS

The problem of measuring the sizes of individual raindrops has been considered and attempted since 1904 when Bentley placed a one inch deep layer of fine flour on the bottom of four-inch diameter, open-topped, cylindrical containers. He exposed his containers to natural rain and retrieved them as soon as he felt that he had collected a sufficient sample. The miniature dough balls thus produced were allowed to harden untouched. Then they were removed from the layer of flour, brushed free of excess flour, and measured individually with a calibrated scale. His method was surprisingly accurate since it represented errors of approximately ±1 millimeter in diameter. Unfortunately, the tiny droplets were subject to proportionately larger errors, and below a certain diameter droplets were undetectable.

Since that time many investigators have attempted to devise techniques to yield both greater accuracies and shorter data processing times. The desire to learn more about the formative stages of the precipitation process has stimulated experimenters to formulate measuring techniques which may be used from the surface to the region of precipitation formation. Understandably, not all precipitation begins as liquid condensations on hygroscopic nuclei, so techniques for measuring smaller and smaller raindrops will not answer all the questions concerning the initiation of precipitation, but such techniques will assist in the interpretation of what happens to a precipitative particle once it has become entirely liquid. At any given time and elevation in liquid precipitation a wide spectrum of drop sizes exists. Investigators must use differently designed instruments for the high and the low ends of this drop-size spectrum. The author will be concerned only with the raindrop end of that spectrum since it is this size range that is most easily detected by centimeter-wavelength, meteorological radars.

There are basically three classifications of raindrop measurement methods. They are:

I. Replica Methods

II. Impact Methods

III. Passive Sensing Methods

In the Replica Method classification, other investigators have attempted to use flour as an indicator besides Bentley with his dough balls. In a later experiment, flour was spread evenly on a fine wire mesh and exposed to rain. As each water droplet passed through the screening, it removed the flour in the same shape as the horizontal projection of the raindrop at the level of the screen. Many problems prevented this method from becoming a standard of drop-size measurements. First, the apparatus was fragile and required precise exposure timing. Secondly, the drop-size information had to be taken immediately after exposure to prevent its destruction by mechanical vibration; or, alternatively, a photograph could have been taken, which later would have had to have been analyzed laboriously. Lastly, the drop-size accuracy was limited by the size of the holes in the mesh and by the angle of incidence of the drops, since raindrops with a slanting incidence would leave an oblong trace in the flour.

A more convenient and portable system has been used by a large number of investigators including researchers here at M.I.T. It is commonly termed the "filter paper technique" even though several surfaces have been used as absorbent collectors. In this method, a piece of absorbent paper treated with a water soluble dye (usually rhodamine, eosin, or methylene blue) is exposed to natural rain. The raindrops form dyed circles which can be calibrated to indicate raindrop diameters. The technique used at M.I.T. is to treat a standard grade of filter paper with Diazo dye and, after exposure to rain, to "develop" the latent raindrop image with ammonia fumes. The resultant image, once developed, is resistant to water soiling and may be stored away for future data reduction.

The "filter paper technique" suffers from many of the same problems that other discrete drop-sampling techniques have encountered. The non-continuous nature of the technique limits the size of the drop sample because of the operational time required between each sample. This objection has been removed in some experiments by mechanizing a continuous roll of sensitized paper such that it passes by an exposure aperture at a prescribed rate and is dried and/or developed before it is wound on a take-up spool.

The obvious shortcomings, especially in the continuous filter paper technique, include the great amount of time required to process the data. Each drop must be measured individually with a calibrated ruler and then recorded. Also, with increasingly higher rainfall rates, it is mechanically difficult to measure the exposure time of the filter paper. (For filter paper eight inches in diameter, this may be as short as one second or less.) Automatic versions of this technique could employ a shutter mechanism similar to that used in a camera except on a larger scale. One additional shortcoming is a reduction of efficiency below roughly 0.7-0.9 millimeters.

Also to be considered a Replica Method is the technique of photographing an illuminated volume containing raindrops and later measuring the drop sizes from the developed film (Jones and Dean, 1953). This method is advantageous in that it permits a sampling of greater than one cubic meter per minute, but it has the same shortcomings as the "filter paper technique" in that it requires long hours of data reduction for each hour of storm data. The Illinois Water Survey investigators have simplified their data reduction problem somewhat by devising electric calipers which may be used to measure the drop sizes and simultaneously provide an output on punched cards. They state that their measurements of 0.5-1.0 millimeter drops are subject to error; however, judging from their plotted results, it seems as if their efficiency of measurement begins to decrease at drop sizes as large as 1.5 mm.

Other physical properties of the drops may be measured to obtain the drop size. One method has been suggested and attempted frequently because it readily yields a measure of the momentum transferred to a sensor by each raindrop. This technique, as employed by Smulowicz (1952), consisted of exposing a diaphragm to the rain and measuring the peak electrical responses of a mechanical-electrical transducer which was connected to the diaphragm by a fluid coupling. The fluid coupling was a major improvement of this device over similar devices since it permitted uniform sensitivity and response over the entire exposed area of the diaphragm. His impact plate had a small enough coefficient of restitution to prevent the secondary showers of smaller drops resulting from the impact of large drops. His diaphragm was constructed of thin neoprene rubber with a central aluminum disc since stiff metal discs, formerly used in impact devices, showed a rapid variation of sensitivity with radius.

One basic limitation of his system was that an impact within a certain time after a previous impact would be counted incorrectly unless an electronic rejection system were employed. This naturally placed an upper limit on the maximum rainfall rate during which the instrument could be used. In terms of liquid water content, this was 4.1 grams per cubic meter. Since the instrument was designed for use in an aircraft, precise knowledge of the air speed of the aircraft was vital at all times to obtain the masses of each drop from the momentum measurements. Also, one meteorological problem not mentioned, since the calibration of this instrument was done with steel balls, would be the detrimental effects of flooding the surface of the diaphragm so that impinging droplets might collide with a water cushion instead of the diaphragm surface, resulting in erroneous readings.

An Australian impact instrument (Cooper, 1950) was balloon-borne and involved the use of a variable-capacitance momentum transducer instead of the microphonic technique employed by Smulowicz.

Earlier, in 1949, A. A. Perez made a theoretical study of the problem of measuring raindrop-size distributions by the impact method and concluded that the problem was incapable of solution.

Two other techniques which require impact but do not use some measure of the impact for measurement are icing-rate meters and the raindrop spectrograph.

An icing-rate meter can yield a drop-size count if an initial drop-size distribution and a collection efficiency for each drop size are assumed. One type of meter works by exposing cylinders of different diameters to air flowing past an aircraft. Supercooled water droplets within the sampled volume collect on the exposed cylinders, which are slowly rotated to present surfaces of circular curvature to the air. The device works on the principle that the smaller the drop the more easily it can follow the streamlines of the airflow around an obstacle. Thus, the larger the collection cylinder, the more small droplets are collected. Successive differencing of the total weights of ice on each cylinder yields a measure of the number of drops in several size categories. The main objection to this technique is that the results are highly sensitive to the original assumptions.

Another interesting technique is the raindrop spectrograph that was constructed by Bowen and Davidson in 1951. They set up a wind tunnel with an aperture at the top for falling rain. Each drop as it fell through the uniform, horizontal air stream was deflected from the vertical by a distance inversely proportional to its mass. The displacements were recorded on filter paper at the base of the spectrograph and thus the data reduction was tedious and time consuming. In addition, the instrument was useful only in vertically falling rain, since any drops with horizontal velocity components produced erroneous displacements in the spectrograph.

All of the previous methods of drop-size evaluation, except the photographic replica technique, have resulted in the destruction of the raindrops. Another class of techniques may be called Passive Sensing Methods since it represents techniques of measuring the drop size without the destruction of the drop or the interruption of the airflow. The principle advantage of this method is that, with droplets passing freely through the sensing device, there is no flooding of the sensor and each drop will encounter a uniformly receptive sensor. This now permits continuous measurements to be taken. Secondly, since the drop is not destroyed, there can be no miscounting of secondary, splash drops resulting from the impact of larger drops. Thirdly, if the airflow is not seriously distorted, most of the drops in the path of the sensor will pass through the sensor and the final output will be a representative drop-size distribution.

In order to use this indirect method, other physical properties of the drop besides its mass or its momentum have been used. Thus far, electric charge, dielectric constant, and optical scattering cross-section are some of the drop parameters which have been chosen.

The electric charge method, as described by Bemis (1951), requires the application of an electric charge to each raindrop as it enters the drop sensor. Further along in the sensor is a charge detector and amplifier system which is capable of measuring the very slight charges on the drops and of differentiating among the various amounts of charge which represent different drop sizes. The technique requires a very sensitive detection system and is limited to measuring drops that carry no charge of their own before they enter the sensor. Unfortunately, circumstances can arise, especially in connection with potential or mature thunder storms, wherein raindrops do possess a separation of charge. When these drops break up, charged raindrops can exist. One of the engineering difficulties of this technique is providing a uniform field over the sensor aperture so that all uniformly-sized drops receive the same charge regardless of the portion of the sensor field that they intercept.

The technique of using the dielectric constant as an indicator, also described by Bemis (1951), consists of designing the raindrop sensor aperture so that the raindrops pass through the two plates of a capacitor which is part of a tuned circuit of an oscillator. The intrusion of a raindrop between the plates of the capacitor represents a change in the dielectric constant of that medium, and, hence, represents a change in the capacity. This slight change in the value of the capacitor is reflected in a change in the frequency of oscillation. This method lends itself to automatic recording of the drop sizes since the variable frequency output may drive directly a pen recorder or a frequency meter with a printer. This instrument is difficult to engineer because the capacitor must be designed so that its response is uniform over the entire plate area. The response due to capacitor edge effects and other non-uniformities must be interpreted correctly by the electro-mechanical automation if the device is to be continuously-measuring and operatorless. Finally, some method of keeping the capacitor plates dry must be employed because any residual drops or splash within the plates of the capacitor will produce incorrect results.

A. C. Bemis (1951) directed a group effort in the production of the Disdrometer, a photoelectric instrument for measuring drop sizes encountered in flight. The device presented a uniform beam of collimated light transverse to the airflow past the aircraft. A photomultiplier circuit was used to view the light beam and to detect any reduction in its intensity, as by the passage of a raindrop. The variations in light intensity caused by raindrop passage were so slight that they were close to being lost in the noise of the circuitry; however, the pulses thus produced were detected, amplified, sorted, and presented on a tally register. Then the register was photographed periodically to provide a permanent record. Many problems plagued the effort from its initiation. As was mentioned before, any reduction in the intensity of the light would give false drop sizes. This meant that the light source had to be maintained uniformly brilliant to within very close tolerances. Meteorologically speaking, though, this meant that no raindrops could be permitted to collect on the optical surfaces and thereby obstruct the light beam. This is almost equivalent to placing a pail out in the rain and requiring that the sides of the pail remain dry. They were, however, able to solve this problem by placing a set of vacuum-fed lips on the leading edge of their sensor and by allowing quantities of dry gas to pass over their optical surfaces and prevent any accumulation of water. With all the gas tanks, vacuum pumps, stable power sources, and recording equipment, this measuring system not only was mounted in a plane for convenience, but required a plane to lift it. Unfortunately, since the information signals were so close to the noise level, the instrument was never an unqualified success. One conclusion that was made as a result of their flights into storms was that the drop-size distribution varies rapidly both areally and temporally; thus they felt that there was no hope of an accurate correlation between comparitively small-scale aircraft measurements and the large-scale radar measurements.

Another drop-sampling technique employed the measurement of light scattered from raindrops as a measure of their size. Dingle and Schulte (1962) developed and operated quite successfully a photoelectric raindrop-size spectrometer. They illuminated a prescribed volume of air with a collimated light source and viewed this volume at an angle as raindrops were falling through it. Then they rotated the whole sensor at 120 revolutions per minute so that they swept out a volume of 0.78 cubic meters per minute.

The last two methods both involved the scattering of a collimated light beam by raindrops. In the first case, however, investigators were trying to measure the difference between two large amounts of energy and the results were therefore subject to larger errors than the second method, which was concerned with detection over a smaller instrument range.

Similarly to all the previous methods, the Dingle and Schulte method encountered several sources of error. The difficulty of producing a uniformly-illuminated, collimated, light beam still remains a problem. Errors arose when drops intercepted the edge of the beam and, therefore, scattered less light than drops of their size should have if fully illuminated. Also, as with other attempts, meteorological problems presented error-producing situations. Large raindrops can change their shape as they fall and sometimes even oscillate between oblate and prolate spheroids. The light scattering patterns produced by drops undergoing such undulations are vastly different from the light scattering pattern obtained theoretically from the light-scattering pattern obtained theoretically from the study of spherical water scatterers. In fact, since these drops oscillate, the amount of light scattered may not be calibrated to yield drop size.

In short, most methods were successful to a certain extent; but no universal, broad-spectrum, raindrop-sizing device had been built which was capable of giving continuous, accurate, drop-siz information at different heights in the atmosphere.

## III. METEOROLOGICAL PERMISSIBILITY AND LIMITATIONS OF THE TERMINAL VELOCITY TECHNIQUE

Since the author employs a technique of drop-size measurement which has not been described previously in the literature, it is necessary to discuss the validity of this method in terms of physical realities.

The raindrop parameter used in this technique is terminal fall velocity. Unlike the two stones that Galileo dropped from the Leaning Tower of Pisa, raindrops of different sizes fall at different terminal velocities.

One might expect that there would be a linear relationship between the terminal velocity and the drop diameter; but according to Hardy(1962) the drop velocity approaches an asymptotic value of roughly 920 centimeters per second for drops greater than five millimeters in diameter. For small diameters, the drop velocity increases rapidly with drop size. The reason for this is rooted in a complex analysis of the various forces to which the drop is subject. Frictional drag, surface tension, and gravity are the principle forces involved. The larger the drop is, the smaller the ratio of surface area to volume, and hence mass, will be. This results in the inability of the surface tension of the drop to keep it in its spherical shape. Then, the bottom portion of the drop will flatten, present more air resistance, and slow the drop below the speed of an equivalent, falling sphere. Visual proof of this theory has been provided by the studies of Magano (1954) and Jones (1959). These investigators have taken high-speed photos of large drops at terminal velocity and have noticed that the large drops are flattened on the groundward side. From the high-speed photos (Hardy, 1962, Fig. 2, p.3) it appears that the terminal velocity reaches an asymptotic value when the drop presents a nearly-flat lower surface to the airflow.

The relationship between the terminal velocities and the diameters of raindrops has been well established by investigators such as Laws (1941) and Gunn and Kinzer (1949). The author has used a composite of data points for his relationship between terminal velocity and drop diameter. Values have been used from the work of Landsberg et al, Gunn and Kinzer, and from the First Technical Report of the Weather Radar Project of the Department of Meteorology at the Massachusetts Institute of Technology (See Fig. 1).

It is seen from the very slight scatter of points around the line in Figure 1 that this graph provides a one to one correspondence between terminal velocity and drop diameter within a very slight degree of error. Thus, if we can measure accurately the terminal velocity of fall for raindrops, then we may convert these values directly to raindrop sizes.

There are two possible objections to this technique. First, a raindrop may be falling at its

## Raindrop Terminal Velocity vs. Diameter

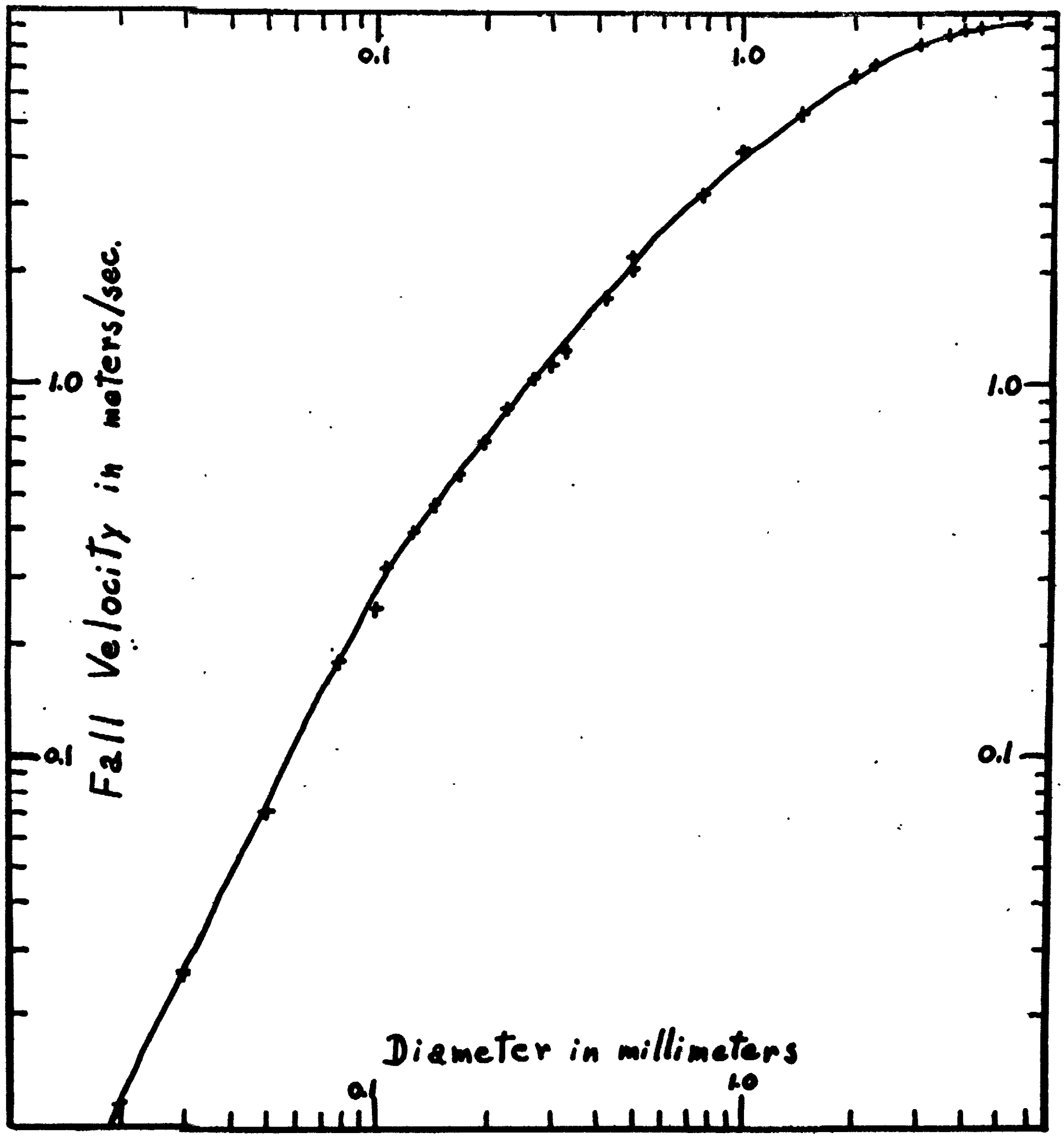



Figure 1

proper terminal velocity with respect to its immediate environment of air; but, if the parcel of air containing the drop possesses a component of vertical velocity, then there would be an error in our measurements if our device were measuring with respect to the ground. The balloon-borne model of our device could be insensitive to larger scale vertical circulations if the balloon and instrument package followed the movements of the air exactly, and, if the cord connecting the instrument to the balloon were not long enough to extend into a region of different vertical velocity. A second possible objection is that, after only a preliminary consideration, it appears that the instrument may measure incorrectly the velocities of raindrops with a slanting incidence to the sensor. A more thorough consideration of the mechanics of the falling raindrops shows that a raindrop appears to have a sloping incidence to the ground because of the horizontal velocity imparted to it by the air in which it is imbedded. Since the raindrop is not passing through the air in the horizontal direction, but merely following its motion, the horizontal component of raindrop fall speed relative to the stationary earth does not represent a vector addition to the vertical fall speed for the purpose of computing limiting fall speeds through air. A possible exception to this reasoning may arise during periods of high-velocity, small scale turbulence when the raindrops do not have time to achieve the local air velocity before they have fallen into a region of different local air velocity.

Thus, during all periods of rainfall except those involving severe local turbulence, the terminal velocity technique may be employed to measure accurately raindrop-size distributions.

## IV. DESCRIPTION OF THE INSTRUMENT

### A. SIMPLIFIED OPERATION OF THE RAINDROP-SIZING SYSTEM

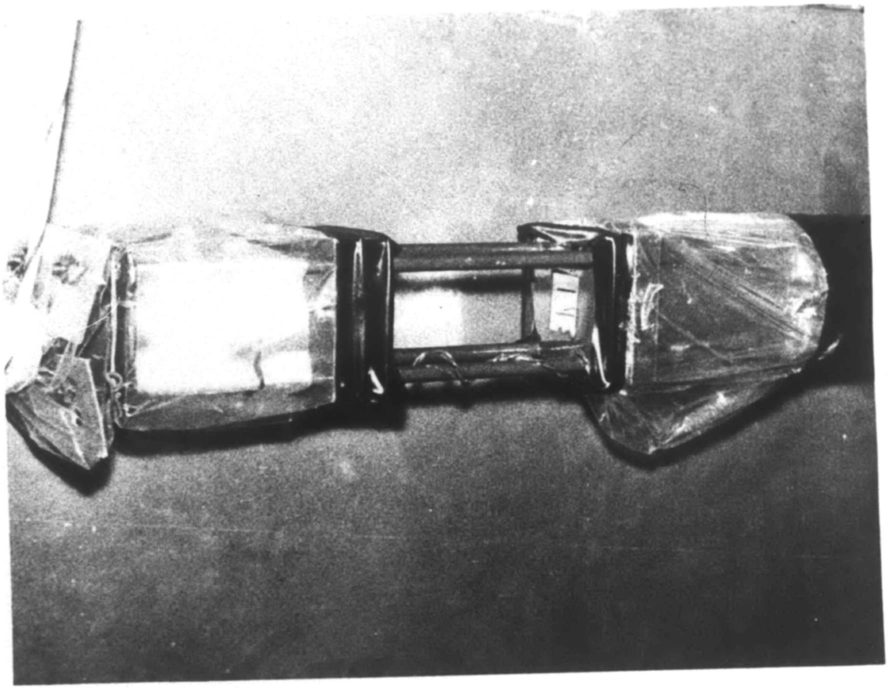
The sensor portion of the instrument consists of two, 1 by 15 millimeter, collimated light beams placed directly over one another with a one centimeter vertical separation. (See Figures 2 and 3) The light beams traverse a 10 centimeter air gap and are recollimated and focused individually on cadmium selenide photoresistors. Any obstructions to the light beams change the values of the photoresistors. If the photoresistors are biased with a high enough voltage, small interruptions of the light beams will produce small voltage pulses in the circuit. These must be amplified to be useful.

Fundamentally, each raindrop falling through the upper light beam sends a pulse through an amplifying circuit and switches the state of a two-state device. As the same raindrop passes through the lower light beam, another pulse goes through a second amplifier and returns the state of this bistable multivibrator to that which it had originally. (See Figure 4)

Now we have circuitry which will allow us to time the passage of each raindrop through a one centimeter, vertical gap. The output of the bistable multivibrator may be used to turn on and then off timing circuitry which has input requirements in excess of that provided by the tiny pulses from each raindrop.

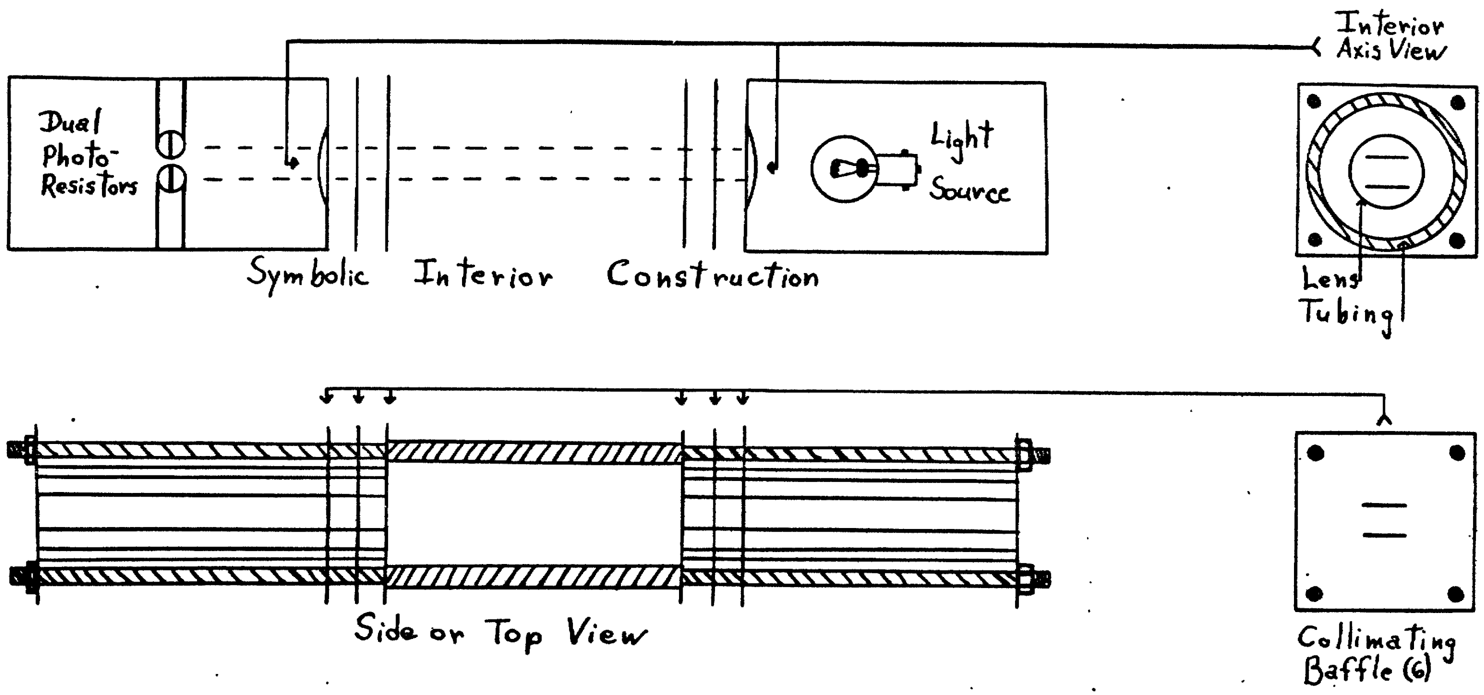
Since the collimated light beam is 1 by 15 millimeters, the circuitry has to respond to a reduction in light intensity of less than 3% in order to "see" the passage of a 0.5 millimeter drop. How much less than 3% depends on the light transmission characteristics of the particularly-shaped droplet that we are measuring. To elucidate further the difficulty of designing reliable circuitry for this purpose, it is well to remember that a 0.5 millimeter drop falls at 1.92 meters/second and takes 5.2 milliseconds to fall through the one centimeter gap. Since the light beam is only one millimeter thick, the pulse produced by the raindrop passage is only 0.52 milliseconds in duration.

The idea of timing the passage of a raindrop through a measured vertical displacement is the fundamental conceptual difference between this method and other methods of raindrop sizing.



<u>FIGURE 2</u>

This is a photograph of the raindrop, terminal velocity sensor. The unit is capable of being mounted either on a surface model or on a balloon model. A permanent version of this test model would have a lightweight, waterproof housing instead of the expedient waterproofing shown here.




# Figure 3

## Scale Drawing of the Raindrop Sensor

1inch = 6 centimeters

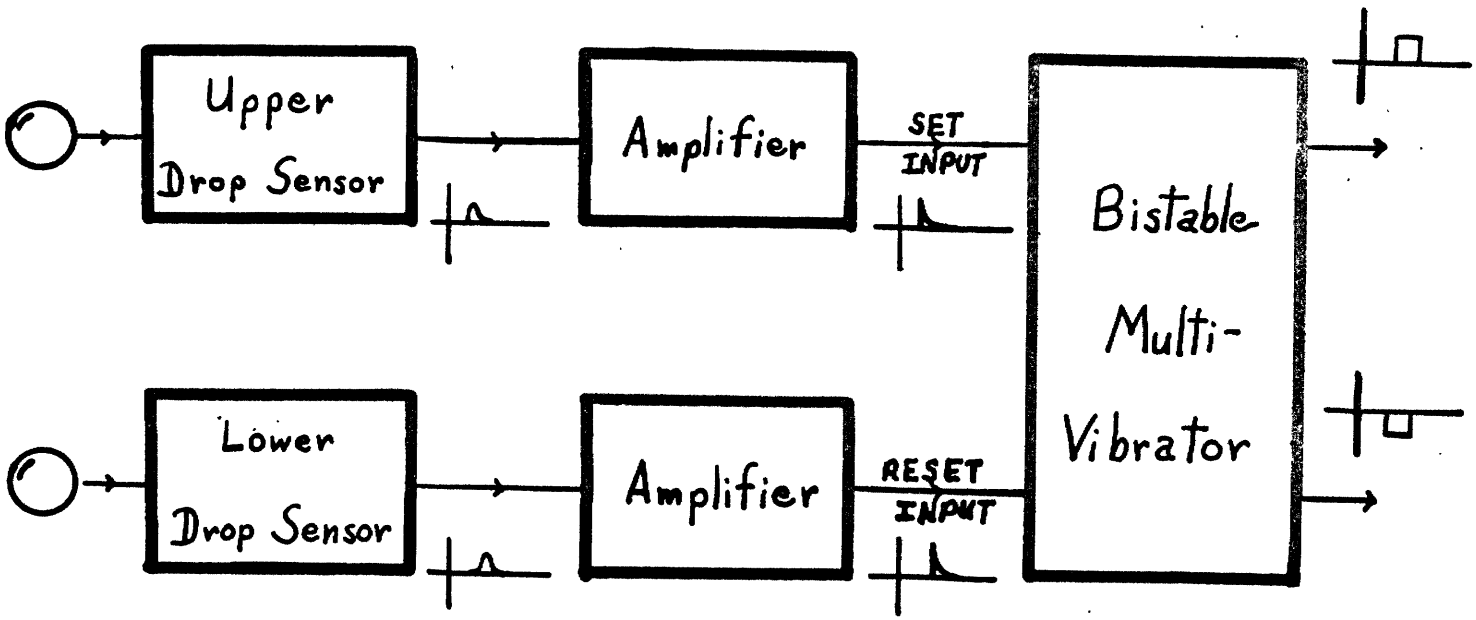



Figure 4
Raindrop Transit Time System

## B. DESCRIPTION OF THE ELECTRONICS

The previously described sensor (Figure 2) was mounted on the end of a 12 foot pole and extended through a sixth floor window for testing purposes during rain storms. The permanent, surface model of this sensor (See Section E.) will be mounted on a pedestal and secured to an unobstructed portion of a roof top. The test mounting was unsatisfactory for accurate measurements except in calm situations because the wake of the airflow around the building contained excessive vertical motions.

Thus we have separated the sensor portion of the electronics from the amplifiers and the bistable multivibrator by long cables. This necessitated the use of shielded cabling for all interconnections to minimize the effects of electronic, background noise. This problem of unwanted noise entering the system has plagued the project from its inception. In the final model it has been necessary to shield completely all of the electronics and all of the interconnecting wires to prohibit their functioning as antennas.

Both amplifier sections of the electronics and the bistable multivibrator have been mounted on a fiberglass circuit board. Figure 5 shows three stages in the development of the electronics. The size of the electronics has been reduced to permit mounting in a standard radiosonde vehicle, and the

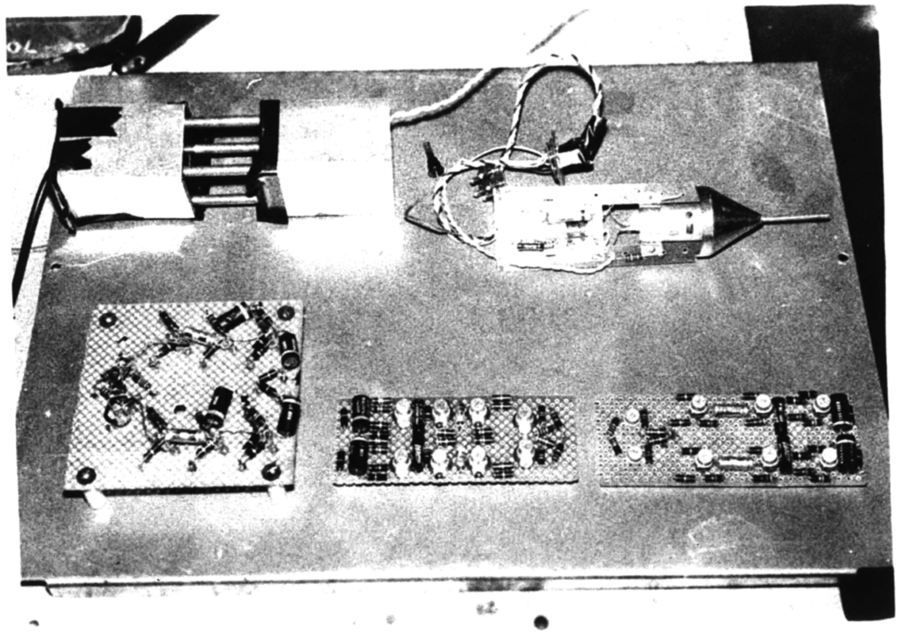


FIGURE 5

Developmental models of the sensor, modified radiosonde transmitter, and three successive models of the electronics.

layout of the parts has been made more orderly to facilitate trouble-shooting.

Figure 6 shows the final surface model of the electronics. It is this model which has been used during many of the tests described in Section VII. The operation of this device may be understood by tracing through the illustrated circuit diagrams drawn in Figures 7 and 9. The photoresistors change their resistance from 11 million ohms in total darkness to approximately 125 thousand ohms with the illumination which we provide. The passage of a raindrop, of course, only permits a fraction of this change; but,with the 90 volt photocell bias voltage, a small pulse (2 volts for a 3.3 millimeter,artificial raindrop, See Figure 8) is produced and is fed to a voltage amplifier and a current amplifier by means of an emitter-follower circuit to provide for the necessary, high to low, impedance matching.

The amplified pulse from the upper drop sensor is applied to the junction labeled A in the diagram of the bistable multivibrator (Figure 9). This switches the output of the multivibrator from 0 volts to 12 volts. The output remains at 12 volts until a second amplified pulse, from the lower raindrop sensor, arrives at the junction labeled B. The output then returns to 0 volts, as referenced to the common ground of the system. This is illustrated in Figure 10. The first drop pulse changes the output from 0 to 12 volts and, 2 milliseconds later, the second drop pulse resets the output to 0 volts.

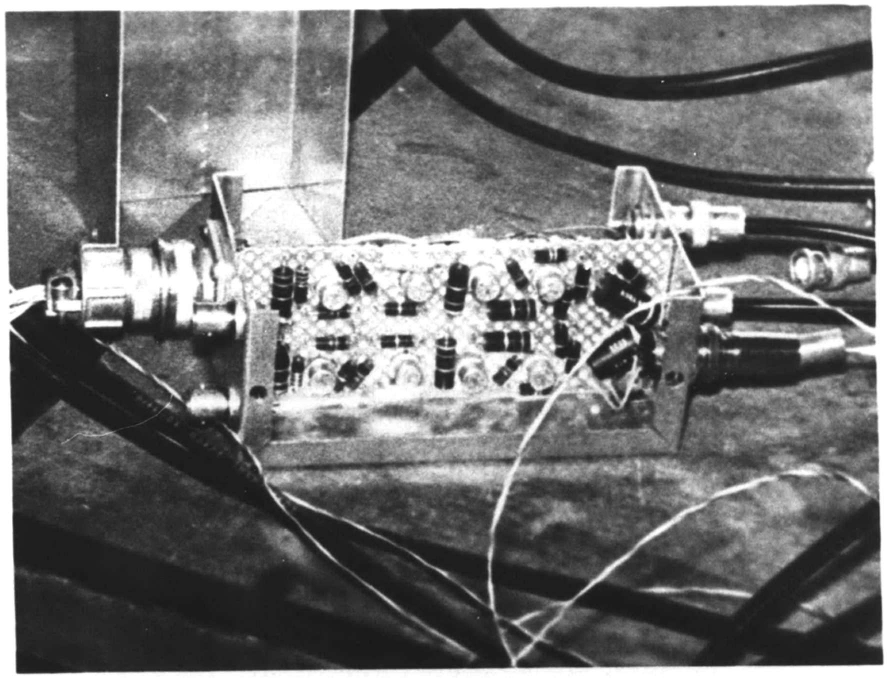


FIGURE 6

This is the final form of the electronics for the surface model. The aluminum case acts as a shield to keep out unwanted, electronic noise. The cables connected to the right end of the illustrated box of electronics extend to the end of the sensor pole. They carry the power for the light source and the raindrop information pulses. The large connection on the left supplies the power to run the electronics. The two smaller connections carry the output to recording devices.

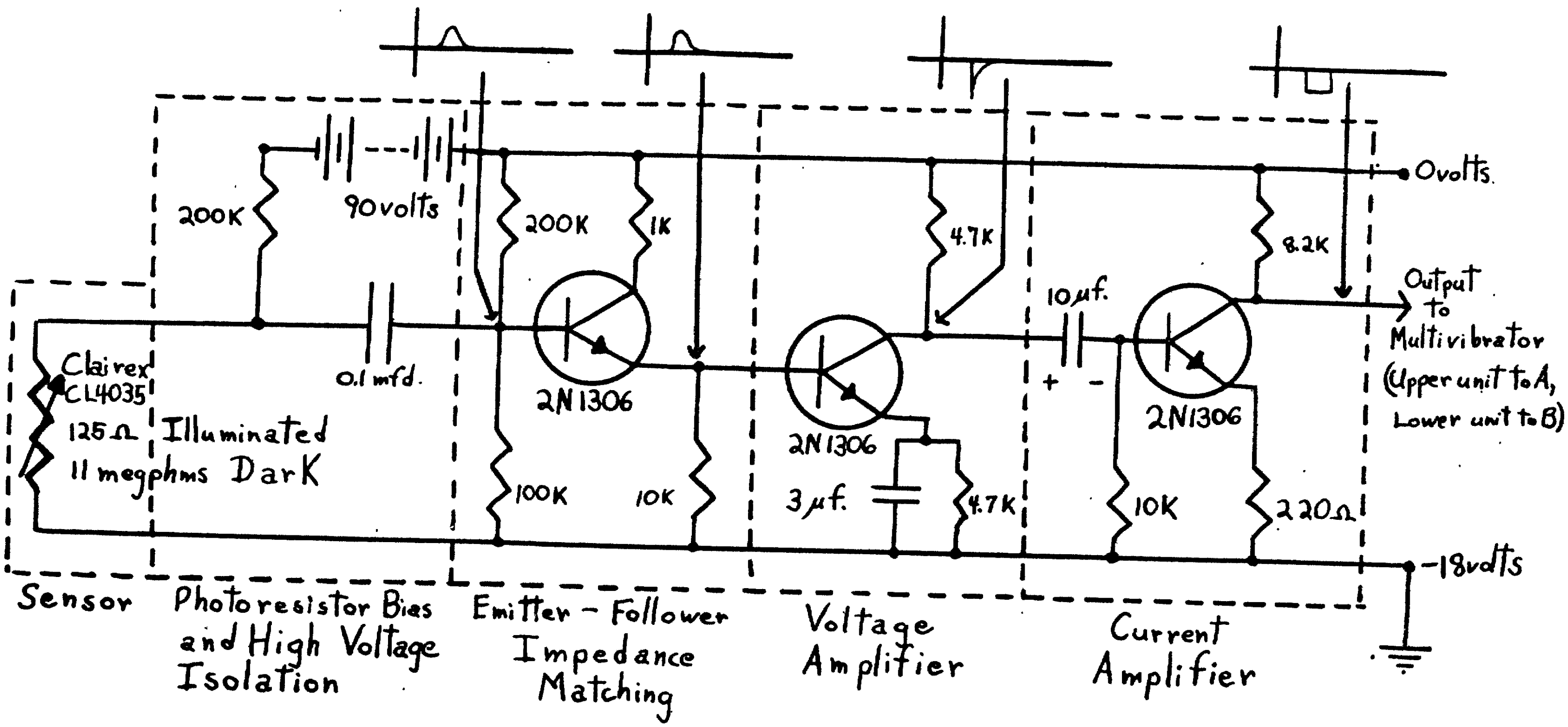



Figure 7

Pulse Amplifier Section

(Two required)

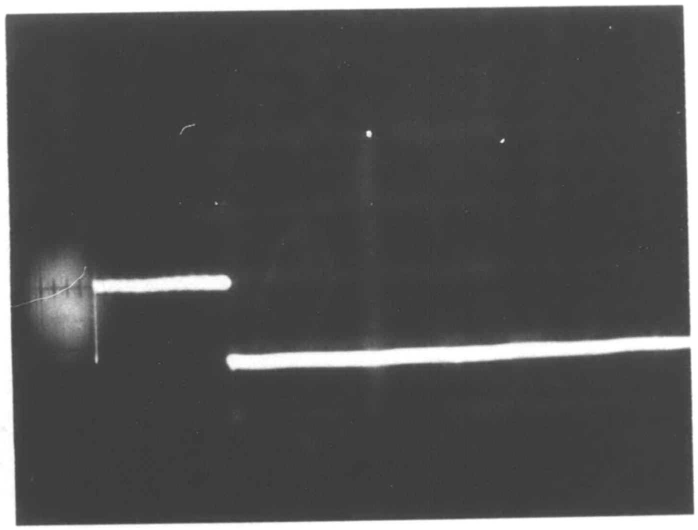


FIGURE 10

The output of the bistable multivibrator as an artificial, one millimeter in diameter, metal raindrop is dropped through the sensor. (10 volts/division in the vertical; 1 millisecond/division in the horizontal)

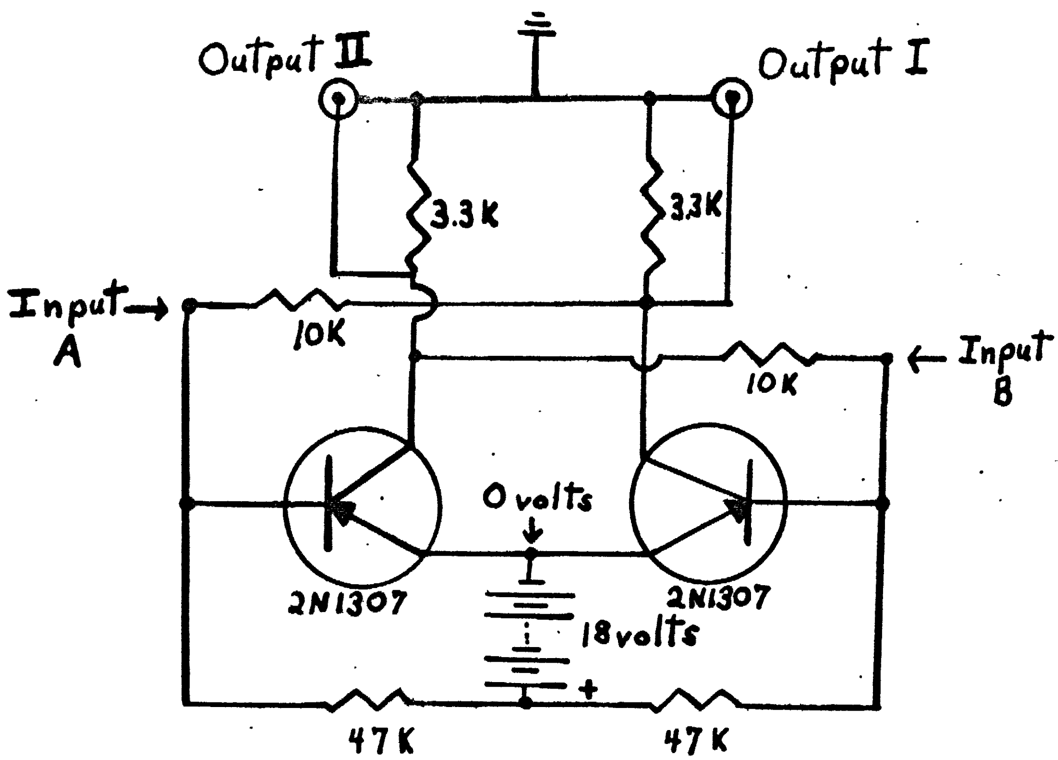



Figure 9

Multivibrator (Bistable)

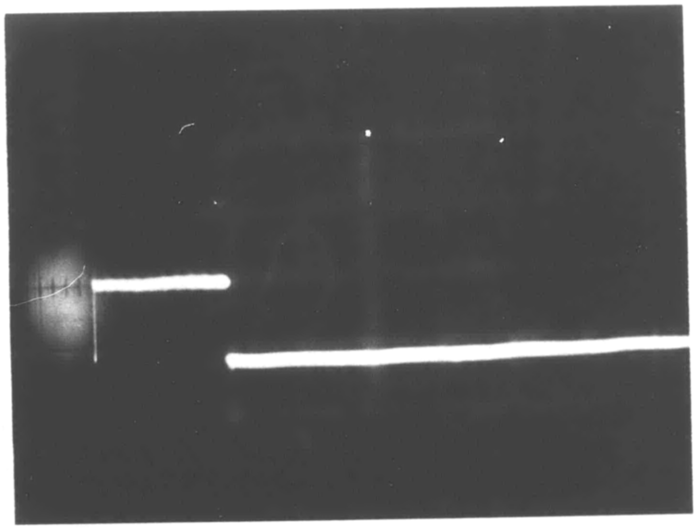


FIGURE 10

The output of the bistable multivibrator as an artificial, one millimeter in diameter, metal raindrop is dropped through the sensor. (10 volts/ division in the vertical; 1 millisecond/division in the horizontal)

## C. RECORDING TECHNIQUES

Many techniques have been envisioned to convert the output of the bistable multivibrator to one which may be read at a slower speed and thereby recorded.

The first technique of measuring the duration of the square wave output from the multivibrator was to connect an oscilloscope to the output terminal. When the oscilloscope was set to trigger its own sweep with any positive increase in voltage, then the pulse length was clearly visible as a square wave beginning at the left edge of the oscilloscope screen and ending at a place on the oscilloscope grid which corresponded to the duration of the pulse. If one knew when the drop were coming, one could open the shutter of a camera and photograph the waveform (See Figure 10). However, in natural rain, drops come at random time intervals and some mechanism to open the shutter of the camera when the drop intercepted the upper light beam would be necessary to have a record of the transit time of each drop.

This method of photographing the waveform on the oscilloscope of each drop was used only in the analysis of the performance of the equipment and as visual proof of the success of the instrumentation.

Continuous use of this technique would be a very expensive project because not only would one have to pay for the purchase and development of one frame of film for each raindrop, but one would have to employ an operator to look at each frame and record the transit time of each drop. The author is certain that if no other technique could have been found that was easier and more economical, that some simple, electro-mechanical device could have been constructed to scan the film and measure the duration of the pulse.

An alternate technique was used to record drop samples from one storm. This technique consisted of connecting the output of the multivibrator directly to the input of a high-frequency tape recorder. The high-frequency model was chosen because its fast rise time gave a sharp spike at the beginning and at the end of each pulse, even though the resultant wave form was differentiated (See Figure 11). Although this was the only recording technique available to the author at the time, it suffers from the same drawbacks as the previous method. The only advantage that it has is that if two drops traversed the sensor within a fraction of a second, it is doubtful whether or not an operator could see and record accurately the two times displayed on an oscilloscope. However, with the recorder, the tape can be replayed to view the waveform of each drop.

Another method was designed, but never employed, to have a record which could be interpreted rapidly by a machine which would automatically place

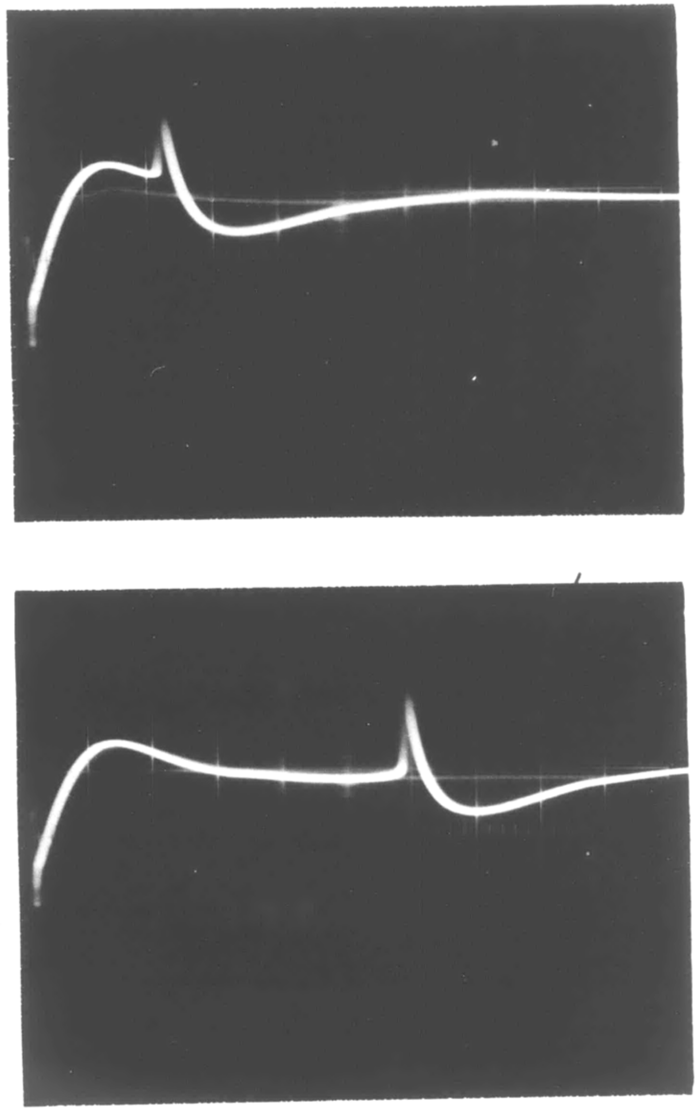


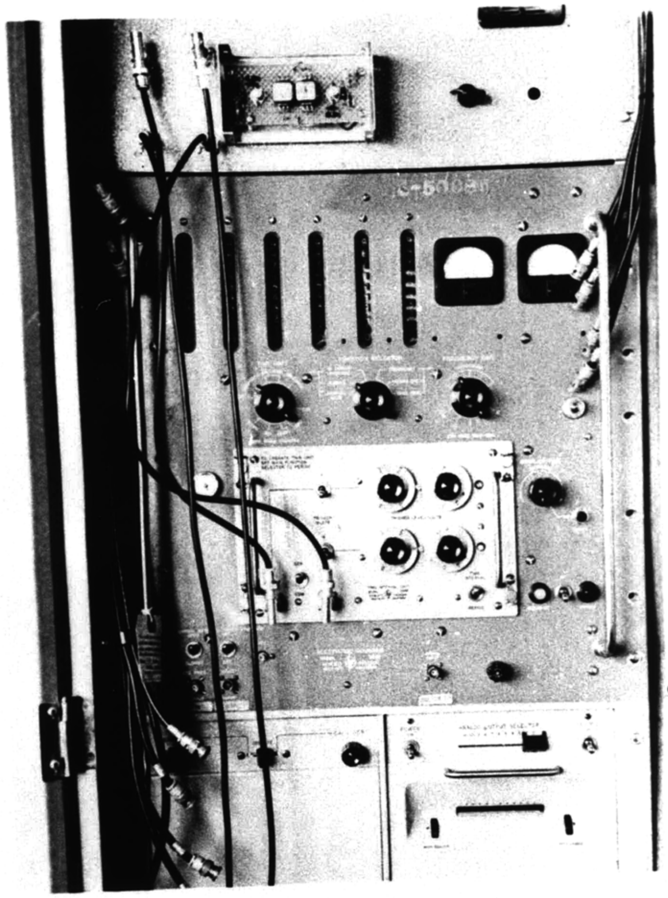
**FIGURE 11**

The waveforms shown above were photographed from an oscilloscope which was receiving information from a magnetic tape recording of natural rain. The distance between the negative and the positive spikes indicates the transit time of the drops. (1 division = 1 millisec.)

the transit times into categories and, thereby, simplify the job of counting. It consisted of having the start of the square wave output from the multivibrator trigger a slow sweep on the oscilloscope and the end of the square wave reset the scope. Recording would be accomplished by passing photographic film perpendicularly to the sweep by means of a slit camera. The processed film would have a horizontal baseline until a raindrop entered the sensor. Then the transit time of the raindrop would be recorded as the height of the line that the sweep traced out perpendicular to the baseline. Thus, the final record would be a horizontal lime with many vertical spikes of varying heights. Automatic analysis of this record could have been accomplished easily by passing the film through a light beam-photocell gap at different distances from the baseline. The output of this circuitry, if applied to a counter, would yield the number of drops in a certain category with each pass of the film. A more ambitious project would have included several light beam-photocell circuits and would have accomplished the counting in one pass of the film. Unfortunately, this technique suffers from the logarithimic nature of the terminal velocity-drop size relationship (See Section VII) and makes it difficult to distinguish among the sizes of raindrops important to radar meteorology. If the scope is set to display over 10 centimeters the transit times of drops as small as 0.2 millimeters, then the times corresponding to drop diameters from 1.2 to 5.2 millimeters are crowded into a space of one centimeter. The necessary conclusion was that the transit times had to be recorded electronically and displayed digitally for the instrument to be valuable over the extent of its sensitivity.

The next recorder design was one which converted the square wave output of the multivibrator to a pulse with a calibrated vertical height. Level selecting circuitry separated the pulse heights into six categories, corresponding to six drop-size categories. The number of pulses in each category was displayed by a series of illuminated-numeral columns. These columns were then to be photographed automatically after the passage of each drop by one of our single-advance cameras. Construction was begun on this equipment, but later set aside after the Weather Radar Project acquired on loan an automatic electronic counter and printer.

The final method enables the operation of drop counting to be made completely automatic and operatorless. The newly-acquired, Hewlett-Packard, electronic counter and digital printer (See Figure 12) has allowed us to time directly the duration of each square wave and display the result in both lighted numerals and on a permanent, paper record. The passage of each drop results in the printing of one line of



<u>**FIGURE 12**</u>

Front view of the Hewlett-Packard electronic counter (center), the paper printer (lower right), and the blocking oscillators (upper left).

numbers on the tape corresponding to the transit time in microseconds.

The direct connection of our multivibrator to the electronic counter did not work because the rise time of the pulse (2 microseconds) was not fast enough to trigger the counter.

Our next job was to devise a system of improving the rise time of the pulse. The system that was chosen was a pair of blocking oscillators between the multivibrator outputs and the counter inputs. The devices increased the rise time of the pulse to 500 nanoseconds, and enabled the counters to turn on and off. Our blocking oscillators (See Figures 13 and 14) each respond to a positive signal change; therefore, we connected one to each output of the multivibrator. The cable connected to the output providing a positive square wave was connected to the start input of the counters because a positive signal change occurs at the beginning of the square wave. The stop input of the counters was then connected through the other blocking oscillator to the output of the multivibrator yielding a negative square wave. In that way, the positive signal change occurred at the end of the square wave, the blocking oscillator reacted to the voltage increase, and the counters turned off at the proper time.

This final method, with its paper tape output still requires the conversion of the transit times to.

drop sizes. Counters are available which will record their output directly on magnetic tape. The use of magnetic tape would permit computer sorting and averaging of the drop-size data and would result in a completely automatic system.

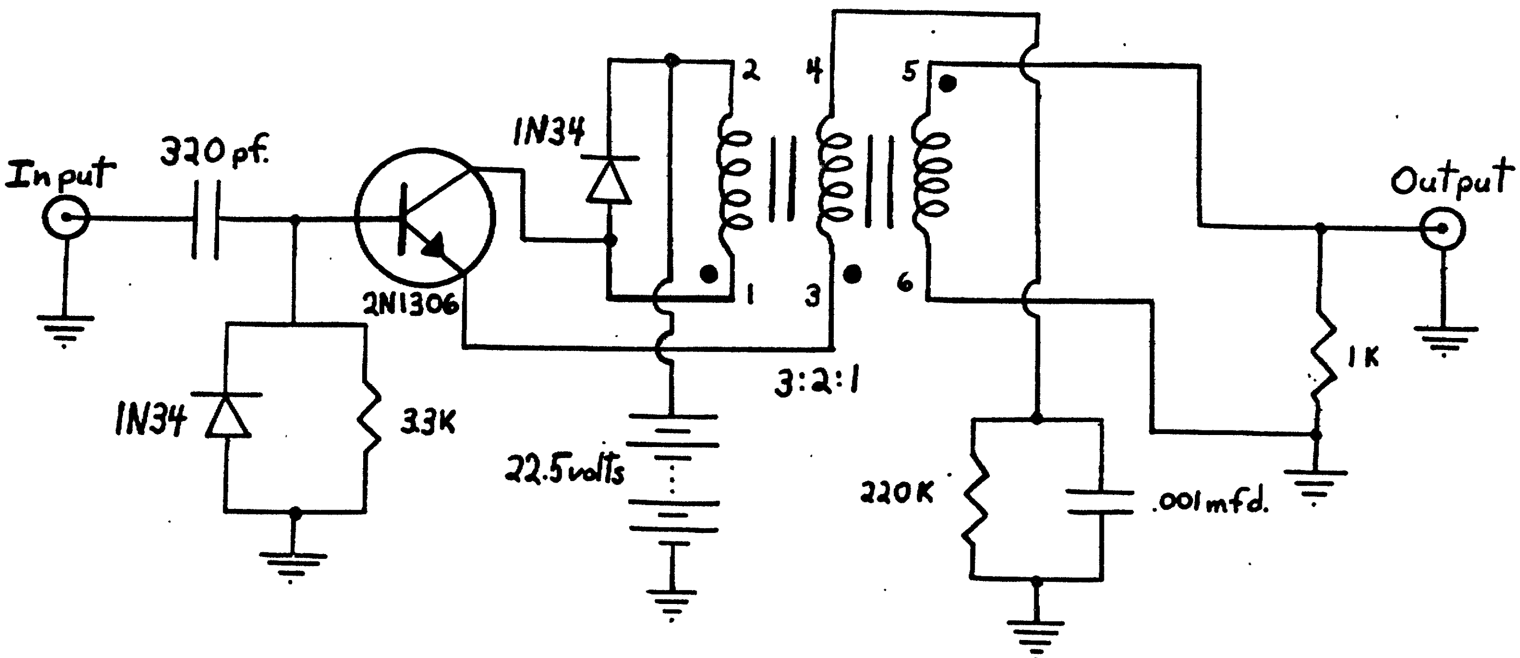



Figure 13

Blocking Oscillator

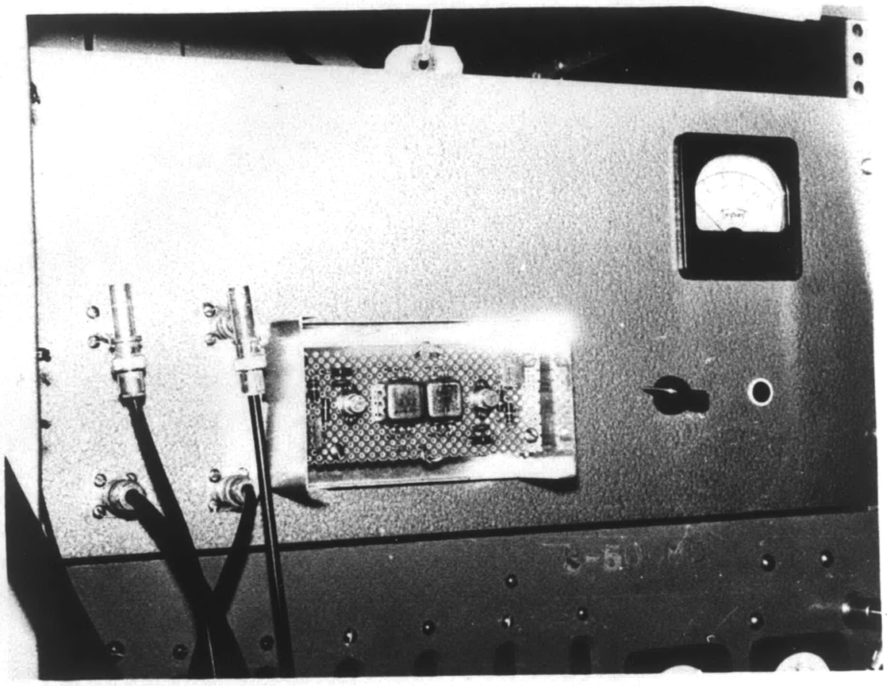


FIGURE 14

Panel view of the blocking oscillators.

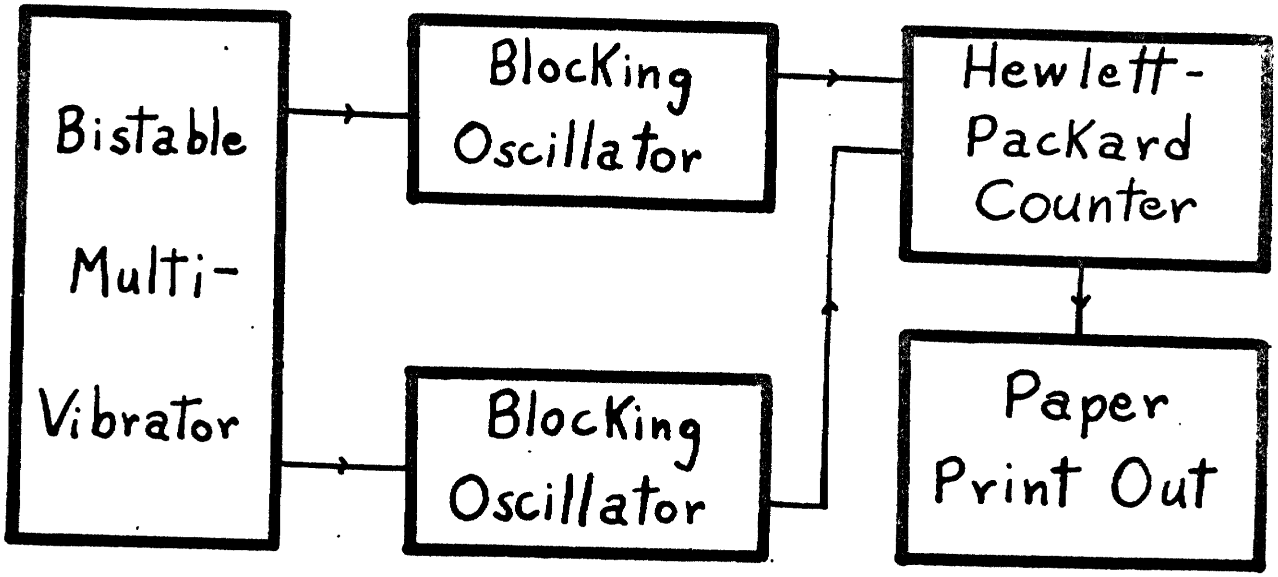



Figure 15
Automatic Recording System

## D. THE BALLOON-BORNE MODEL

The original intent of this project was to design and build a raindrop-sizing instrument to be carried aloft by a standard radiosonde vehicle. It is for this reason that construction materials have been chosen carefully to minimize weight. Since there would be a low percentage of return on non-expendable devices, it was deemed necessary to design an expendable, telemetering device. This meant that the minimization of cost was also a vital consideration. The economical aspect of the requirements is facilitated by the supply of meteorological balloons, helium, and radiosondes available for student research in the Weather Radar Project.

Our standard radiosondes transmit their information on temperature, humidity, and pressure back to the surface by appropriately modulating the radio carrier frequency from which they are tracked. The raindrop-size telemetry problem concerned with the balloon-borne model was solved by replacing the normal radiosonde modulation circuitry by a direct connection to the output of our multivibrator. In this way, the transmitter emitted a constant carrier frequency until a raindrop intercepted the uppermost of the two light beams. The transmitter was then deactivated by the 12 volts from the output of our circuitry. The transmitter remained off until the raindrop passed through the second light beam. Then transmission was resumed. (See Figures 16 and 19)

Two other modifications to the radiosonde electronics are necessary. First, part of the standard baroswitch must be retained operative to insert long interruptions to the carrier frequency whenever a standard pressure level is reached (See Figure 18). This will provide a knowledge of the height of the drop sampler as well as a knowledge of the average rate of ascent between pressure levels. It is necessary to know this rate of ascent accurately because it must be subtracted from the apparent fall velocities measured by the sensor. The resultant fall velocities would correspond to drop sizes. The second modification consists of a time-delay circuit which simulates the passage of a raindrop after a certain length of time. Without this additional circuitry, a raindrop which hit the upper light beam and missed the lower one could turn the transmitter off and leave it off until another drop hit the lower light beam. This would not only make the automatic antenna (See Figure 17) start to search for the signal, but also it would make the telemetry ineffective for the next drop which fell through the sensor.

A simple connection of the raindrop sensor and the associated electronics to a standard radiosonde is not sufficient because the normal, pendulum-like, swings of the radiosonde beneath its balloon would introduce a large number of erroneous transit times because the sensor would be at an angle to the rain. An aerodynamically modified shape of the radiosonde proper has been designed to damp out the local, higher-frequency oscillations (See Figures 20 and 21). Hopefully, this skirt will keep the sensor light beams perpendicular to the cord supporting the radiosonde. The next concern is to keep the cord as nearly perpendicular to the ground as possible. A long cord connecting the parachute to the instrument platform will help prevent rapid swings of the instrument through a large angular displacement from the vertical. A long cord will force any displacement of the radiosonde laterally from beneath the balloon to result in a tipping of the instrument through a smaller angle. The fins and swivel on the balloon-borne model help to keep the instrument from spinning.

There should be no concern about slanting rain in the balloon-borne model. The balloon and instrument will be following the horizontal wind; therefore, the drops should be falling at nearly perpendicular incidence relative to the moving instrument platform. The most critical requirement is to keep the raindrop sensor level with respect to the ground.

The balloon-borne model must have separate, self-contained power supplies for 90, plus 18, minus 18, and 9 volts with low amperage requirements. Also, it must have a 7.5 volt supply which is capable of delivering a current of one ampere for the duration of the measurements to operate the light source. Heavy batteries may not be used because the total weight of the instrument must be under five pounds to be within the F.A.A. restrictions.

Even after designing the instrument to flight specifications and after surmounting many of the difficulties involved with the transmission of the information back to earth, we were forced to postpone work on the balloon-borne model. According to our preliminary testing (See Section V-C), the size of the sampler was not large enough to take a sufficient sample in the time that it would take a balloon to rise from the ground to the freezing level. The attachment of additional sensors would make the weight of the flying model excessive. This coupled with the knowledge that ordinary, radio frequency static could sound much like the carrier frequency interruptions created by our device forced us to concentrate our efforts on an improved, surface model.

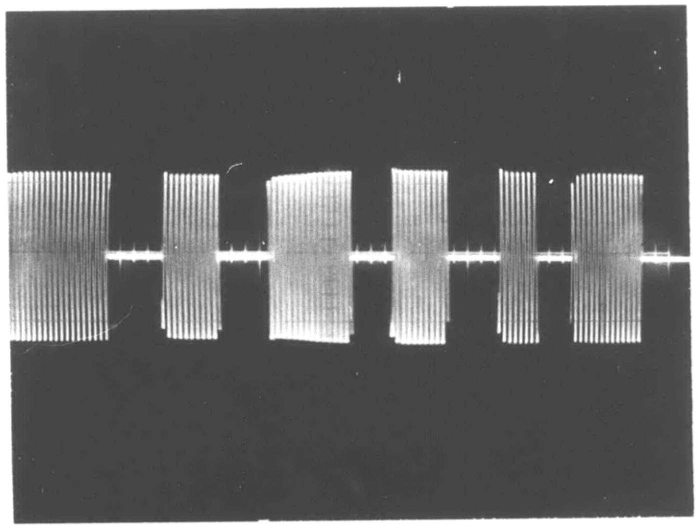


FIGURE 16

This is a simulation of the reception of transmitted raindrop-size information. The durations of the interruptions of the carrier frequency would be directly related to drop sizes after appropriate subtractions had removed the effects of the rate of ascent of the sensor.

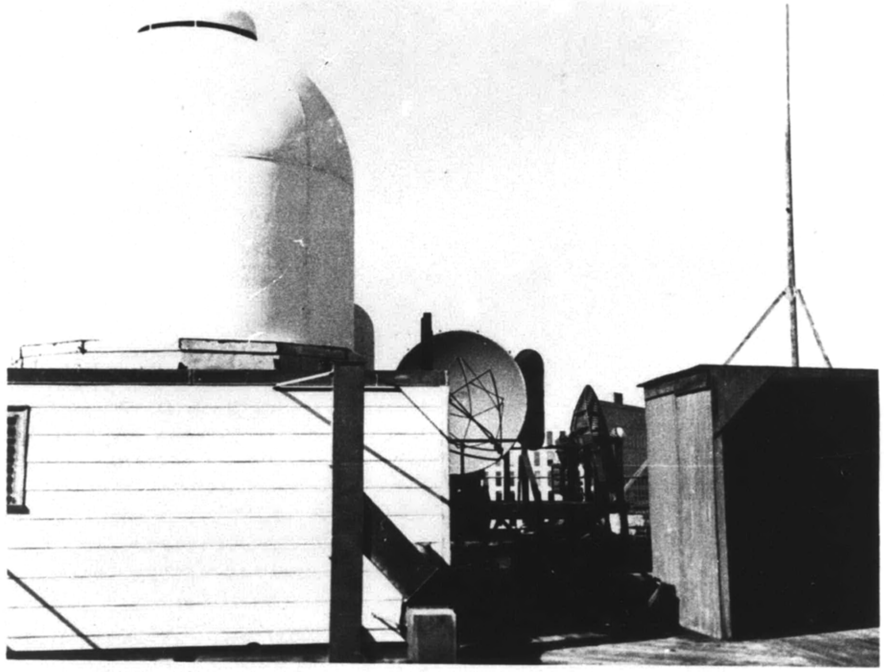


FIGURE 17

The above photograph is a view of the roof-top of Building 24 at M.I.T. Illustrated from left to right are the 10 centimeter and 3.2 centimeter radar antennas, the radiosonde tracking antenna, and the balloon inflation shelter.

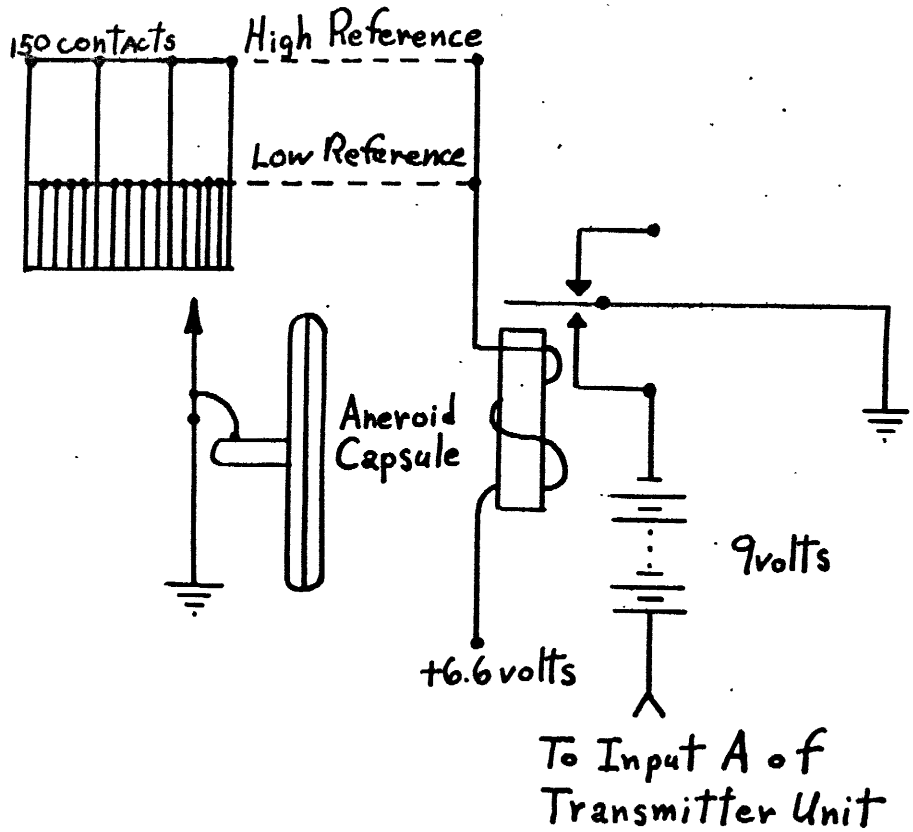



Figure 18
Modified Radiosonde Modulator

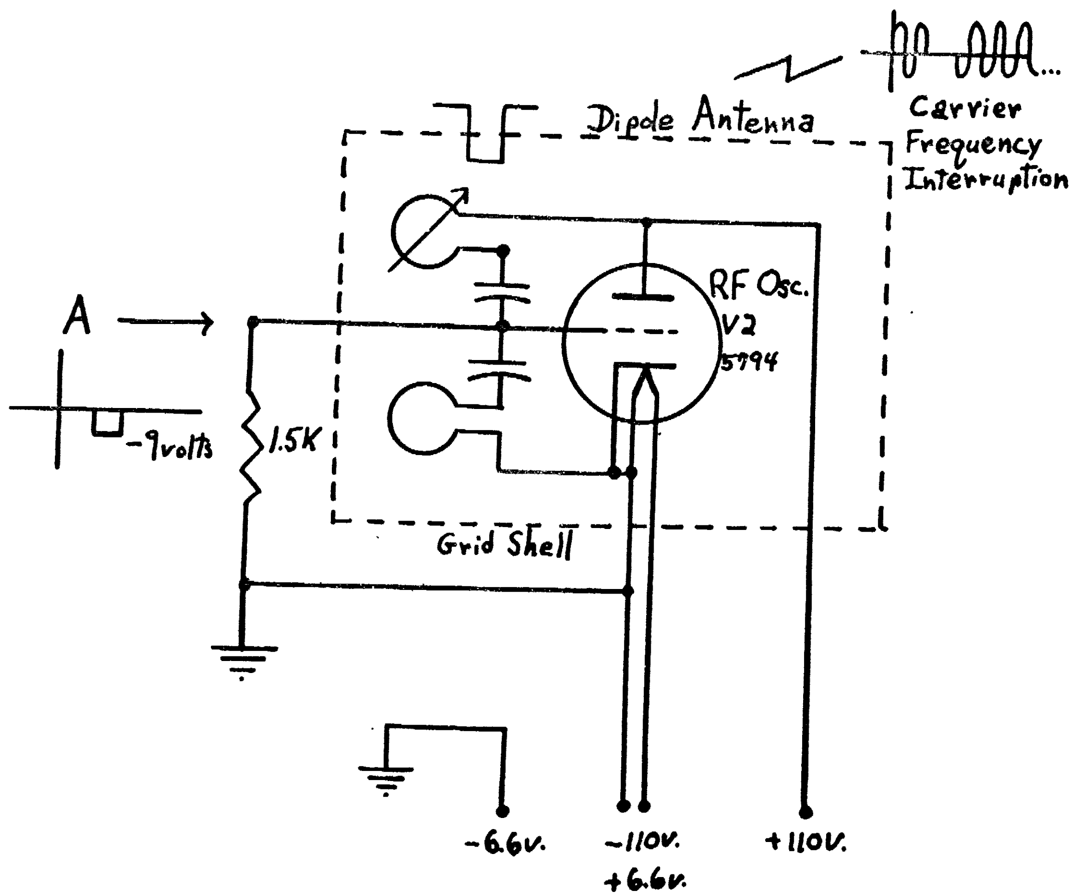
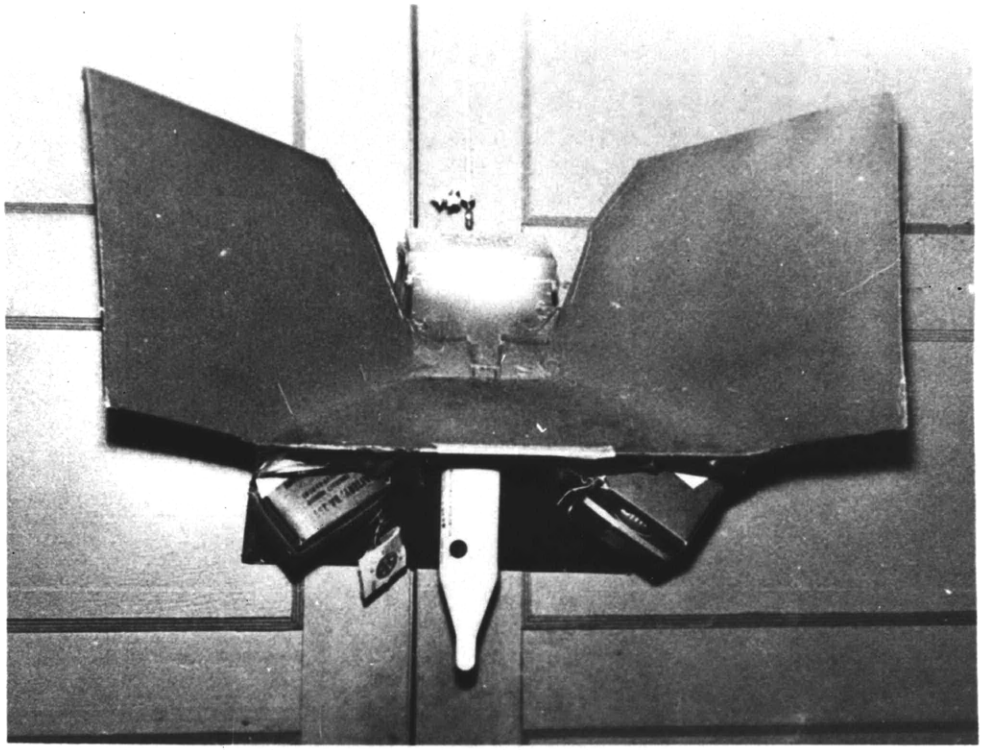
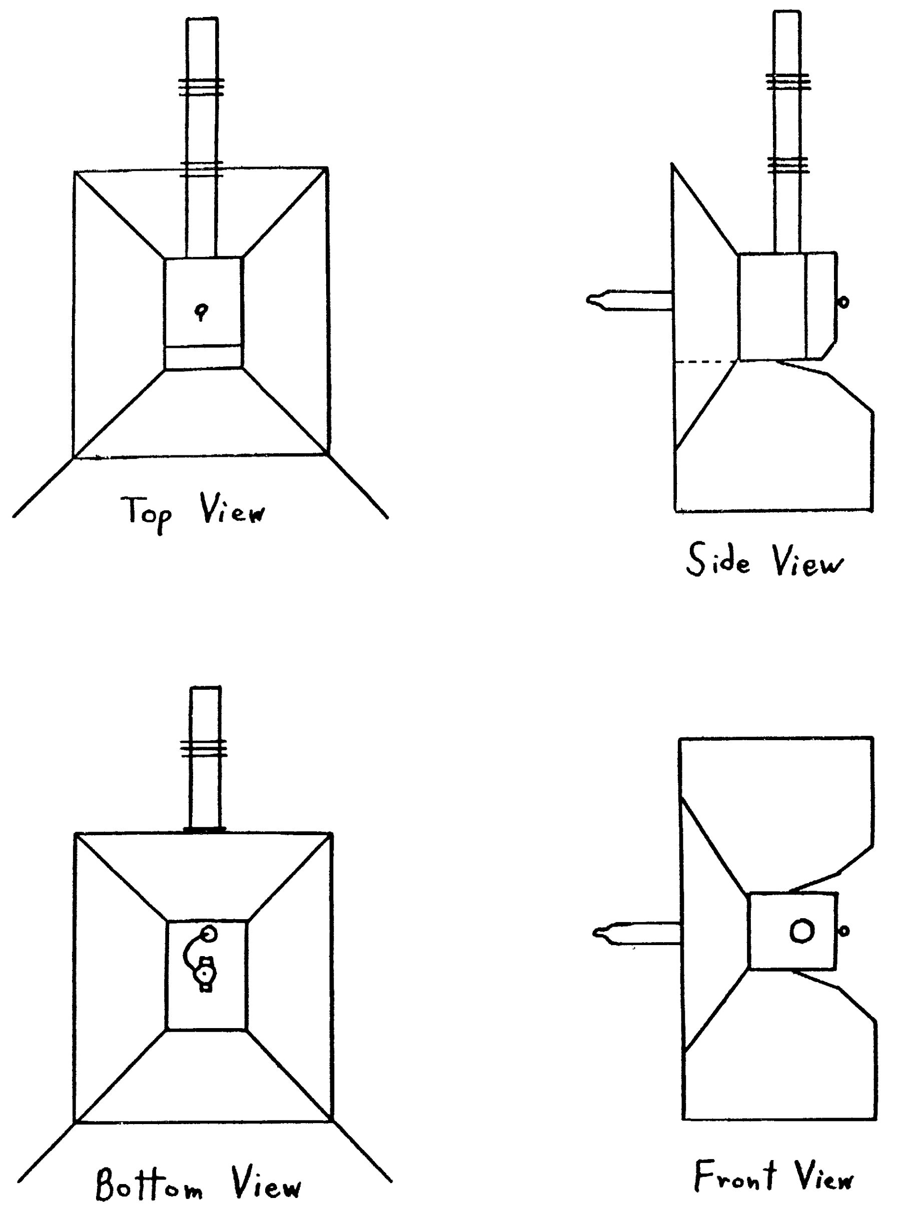



Figure 19
Modified Radiosonde
Transmitter



<ins>**FIGURE 20**</ins>

This is a rear view of the modified, drop-counter, support platform. The purpose of the skirt is to damp out the rocking motions at the end of the cord. The rear fins and swivel are to keep the sensor from spinning and thereby preventing the raindrops from hitting both light beams.




Scale 1:10

Figure 21
Scale Drawing of the Balloon-Borne Instrument Platform

## E. DESCRIPTION OF THE OPERATIONAL SURFACE MODEL

During the construction and testing of the experimental models of the instrument, certain improvements to the original design have been devised. These improvements have been incorporated in an operational surface model of the original instrumentation which will have increased sensitivity, reliability, and accuracy.

Three changes to the original circuitry are incorporated in the operational model. The first change increased both the sensitivity and the accuracy of the final product by increasing the sensitivity and decreasing the reaction time of the photoresistors. An experimental model used to test the feasibility of the drop-sensing technique incorporated photoresistors with cadmium sulphide surfaces. It was found that both the resistance change and the rise time could be increased by using photoresistors with cadmium selenide surfaces. This one improvement has enabled the measurement of drops as small as 0.3 millimeters, whereas the drop-size threshold was formerly closer to 0.7 millimeters.

The second change was found to be necessary after the testing of one experimental model in actual precipitation. In many cases a raindrop would trigger the counter by intercepting the upper light beam and would leave the counter running if that same drop did not intercept the lower light beam, or if the threshold sensitivity of the intercepted portion of the lower light beam were higher than that required to sense the passage of the drop. The non-uniform sensitivity will be eliminated in the operational model, but it is still possible for a drop to intercept the upper light beam and miss the lower one during slanting rain.

In this case the counter will keep running until another drop intercepts the lower light beam, thus printing out an incorrect result. This problem has been corrected by the incorporation of circuitry which will generate a reset pulse at a given length of time after a pulse appears in the upper light beam circuitry. For the experimental model, this was accomplished by means of circuitry within an oscilloscope. The oscilloscope was set to trigger its sweep by the pulse produced when a raindrop intercepted the upper light beam. Simultaneously, the scope started delayed triggering circuitry which was set to provide a pulse ten milliseconds after the initial pulse. In this way, when the lower light beam was not interrupted within ten milliseconds after the upper one had been interrupted, the counter stopped counting and reset itself for the next drop. Incidentally, when raindrops passed through both light beams within the ten millisecond time limit, the additional reset pulse was ineffectual since the drop-timing circuitry required a pulse from the interruotion of the upper light beam before a pulse simulating the interruption of the lower light beam had any effect.

In the operational model of the instrument, it is not necessary to use a valuable oscilloscope just for its delayed pulsing capability. Compact circuitry has been designed to perform this operation. This reset device consists of a monostable multivibrator, which is turned on by a pulse from the upper light beam circuitry and which turns itself off after a predetermined length of time. The output of this device is then differentiated and rectified so that the net effect of the circuitry is to produce pulses, first when the raindrop passes through the upper light beam and then again after a predetermined length of time. This length of time is printed out on the paper record as a recognizably large length of time so that the experimenter has a record of the number of "misses" and can modify the data appropriately.

The final, and perhaps the most vital, technical improvement was the method used to control radio frequency interference. The amplification in the system was so great that local fields of radio frequency energy triggered the drop sizer. Interference from all sources has been virtually eliminated by the inclusion of 0.05 microfared capacitors across all power sources and by connecting the entire system to an absolute ground rather than simply to a common ground.

The operational model of the complete surface instrument incorporates six of the original sensors built into a single unit. (See Figure 22) The resulting increase in the sample area allows the printer to operate at close to its maximum rate of five printings per second for the meteorological condition of very light rain. The number of sensor portions in operation may be reduced to accomodate heavier rain. This operational model includes the original form of the electronics (See Section IV. B.) which has been modified only by the addition of filter capacitors and the reset device as described above. The sensor portion will be mounted on a pedestal atop Building 24 at M.I.T. Cables from the laboratory to the roof will carry the power needed to bias the photoresistors and to run the light sources. Shielded cables will carry the drop-size information from the sensor back to the laboratory. The electronics, including the blocking oscillators, will be mounted on a panel and installed in a movable equipment rack. Monitored and filtered power supplies will be placed behind a second panel. Switches and indicators on a third panel will provide a capability of changing the sample size of the sensor by controlling the light sources and knowing whether or not the proper number of light bulbs is illuminated.

Future intentions of applying the output of the instrument directly to electronic apparatus which will measure the time intervals and sort them into categories, or indirectly to such apparatus through the intermediary mechanism of high quality tape recording may be realized by using the output from the bistable multivibrator. (See Figure 9) The blocking oscillators were needed only to provide a fast enough rise time to trigger the present electronic counter.

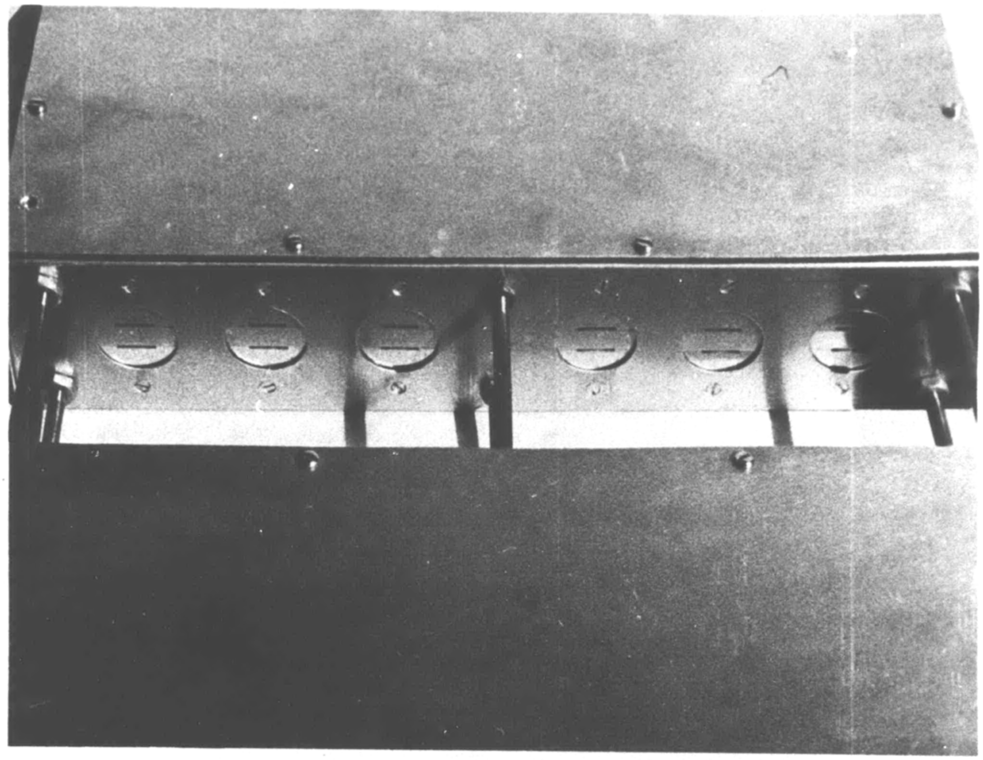


FIGURE 22

This is a top view of the multiple sensor. Any combination or all of the six, raindrop-sensing units may be operated simultaneously to maintain the counting rate of the automatic equipment at nearly five drops per second.

## V. TESTING AND CALIBRATION

During the development of this instrument many tests have been conducted to rate the performance of the individual parts and the phases of the measurement process.

### A. VEHICULAR AND TELEMETRY ASPECTS OF THE BALLOON-BORNE MODEL

It was necessary to know if our radiosonde balloons could lift the nearly five pounds of instrumentation and batteries. Two seven-foot balloons were required to lift the instrument. Fully inflated, these two balloons created enough lift to make the instrument rise at an estimated 1,500 feet per minute. Since it would be desirable to have the balloon rise slowly compared to the terminal velocity of the raindrops, partially inflated balloons could allow ascension rates of 300-500 feet per minute.

Also, it was of deep concern that this five pounds of instrumentation could do considerable damage after the balloon had burst. The normal parachute was tested with a five pound load; and it was found that a single parachute was destroyed in the process of opening. It was decided, therefore, to use a cluster of three parachutes tied close to the balloon end of the balloon-instrument system to preclude the possible occurrence of a three-body oscillation problem.

Other tests were performed with square wave generators to simulate the output of the multivibrator while testing the efficacy of blocking the operation of the radiosonde transmitter by the output of the multi-vibrator. These tests, employing the transmission of two millisecond pulses, thirty times per second, proved that the transmission of drop-size information by this method is possible.

Also, for the flight model, it was necessary to test the effects of interrupting the carrier frequency of the radiosonde transmitter during the worst possible case, that of interrupting the carrier during the total time of the pressure reference connection. Problems could have arisen with the automatic tracking antenna when the radiosonde transmitter was off for roughly five seconds. Fortunately, the antenna experienced no trouble in finding the signal after the carrier interruption. This meant that the present equipment could be used to track the instrument and to receive the drop-size and the pressure level information.

Before a balloon-borne model of the instrument is launched, it will be necessary to launch a mock-up of the raindrop-sizing instrument with a conventional radiosonde payload to measure the rate of ascent of the apparatus under carefully controlled conditions. The arrival of the balloon at each pressure level will be timed and the vertical velocity computed later from the pressure-altitude relationship derived from the radiosonde ascent. It is hoped that this will not be necessary in conjunction with each ascent. Seasonal averages of the pressure level separations or the standard atmosphere pressure level separations could be used with the individually timed ascents between each pressure level to obtain the average rates of ascent for each flight.

B. LABORATORY TESTS

During the development of the instrument, artificial water droplets were needed to test its response and general performance. Initially, repeated drops, 3.3 millimeters in diameter, were produced by a technique employing an elevated reservoir with a flexible capillary tube siphon. This arrangement left the experimenter with both hands free to work on the instrument. Later, a chemistry wash bottle was used because it produced smaller drops, 1.1 to 1.7 millimeters in diameter, at variable repetition rates. A final sensitivity test employed droplets from a one cubic centimeter medical syringe sprayed from a distance of four feet. Filter paper measurements of the resulting drop sizes showed that the range of droplets produced was from 0.3 to 1.2 millimeters. Careful observation of the sample area showed that all of the drops were activating the circuitry.

This device cannot be calibrated with respect to raindrop size in the laboratory simply by measuring the size of a photographic image of the drop. The drop would not be falling at its terminal velocity and, therefore, the relationship between the size of the drop and its terminal velocity would not apply.

Accurate velocity calibration could be obtained by placing the entire apparatus in a darkened room within the field of view of a camera with its shutter open, and by using the same impulse that starts the counter to trigger a photographic strobe light. This method would give a measure of how far the drop must penetrate the light beam before it would trigger the counter. In this way an extremely accurate measure of the vertical distance between the two triggers could be determined and the strobe would produce several images of the drop as it passed through the sampler. The velocity of the drop could be calculated directly from a measurement of the photographic image separations and the repetition frequency of the light.

Actually there is little need to calibrate the instrument in this way because the accuracy of the time calibration of the oscilloscope far exceeds our requirement to measure to the tenths of a millisecond. The only other source of error in measuring the velocity would be an error in measuring the vertical displacement of the two light beams. This has been measured to roughly 98% accuracy.

## C. TESTS IN NATURAL RAIN

A preliminary test of the operation of the initial experimental model of the sensor in natural rain was conducted on December 4, 1964. The output of the bistable multivibrator was connected directly to an oscilloscope set to trigger its sweep upon the reception of a pulse produced by the sensor as it first encountered a raindrop. Times corresponding to drop sizes were then read from the screen of the oscilloscope as horizontal extents of square waveforms. The equipment was operated and data were taken from 09:05 to 09:25 during which time filter paper samples were taken at 09:07, 09:09, 09:11, and 09:13 for the purposes of comparison. The results of this comparison are seen in Figure 23 (a). Unfortunately, the drop-size categories of the two techniques were not the same so Figure 23 (b) has been prepared to facilitate a comparison. In this second presentation the number of drops in each odd 0.1 millimeter category of the terminal velocity technique has been added to the number in the even 0.1 millimeter category just preceeding it. Drop categories with no counterpart in the comparative measuring technique were ignored. The rainfall rate was estimated to have averaged less than one millimeter per hour during the measurements so the numbers of drops collected by both techniques are probably insufficient for significant meteorological samples.

Since this initial sensor did not have a reset device, many slanting drops which hit the upper light beam and missed the lower light beam disabled the apparatus until another raindrop hit the lower light beam. Other drops were missed by the visual observer when many drops passed through the sensor within very short time periods of each other. The resulting data were measured at an average rate of 0.6 drops per square centimeter per

Figure 23 (a.)

Preliminary Comparison of the Filter Paper and the Terminal Velocity Techniques

December 4, 1964

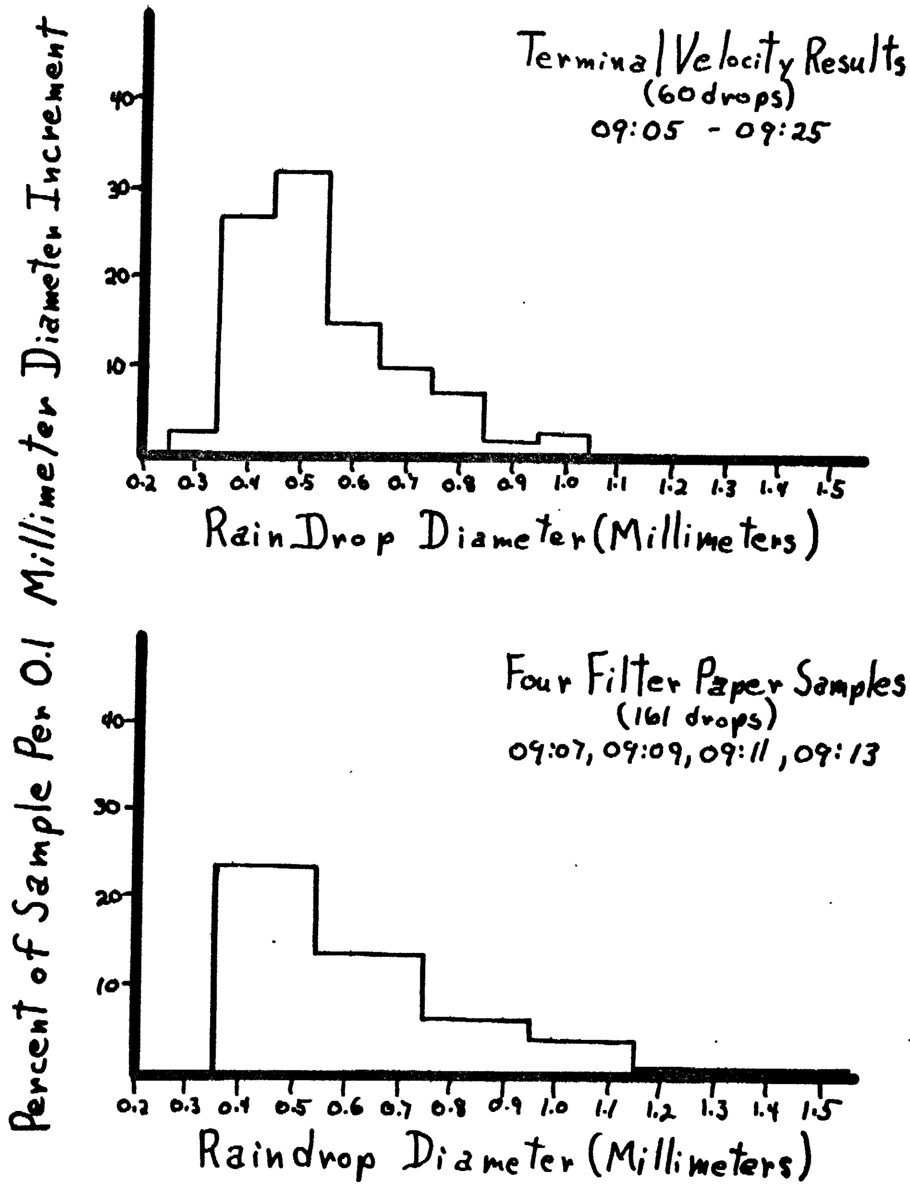
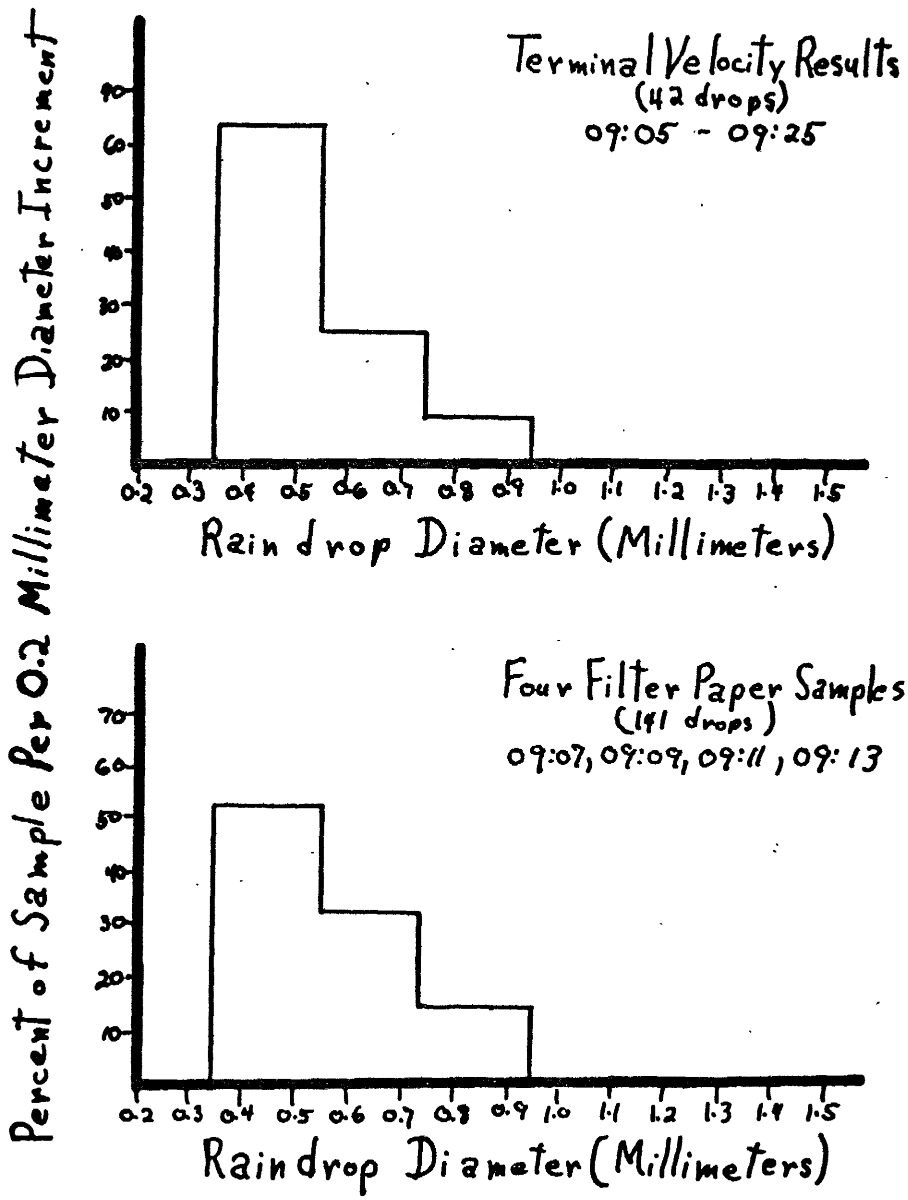


Figure 23 (b.)

Integrated Normalized Results of December 4, 1964



minute whereas the filter paper measurements, taken during periods of comparatively high rainfall rates, were able to average 8.8 drops per square centimeter per minute. This alone provided sufficient stimulus to incorporate a reset device in the circuitry.

The investigation of counting rates made it obvious that, even at full efficiency, the experimental model of the sensor would have an insufficient sampling area to provide adequate samples in short periods of time. In order to estimate the proper sample area for an operational model, a study was performed to determine the average numbers of drops per square centimeter of horizontal area per minute for varying rainfall rates. Drop counts were used from 105 sheets of filter paper exposed from January to May of 1964; the results are given in Table 1.

The present automatic printer has a maximum printing rate of five printings per second. The study described above showed that a sensor with its sample area variable from one to six times that of the experimental model would be capable of measuring rainfall rates from 0.5 to 24 millimeters per hour at an average rate of approximately 2.6 drops per second by compensatory variation of its area to suit the rainfall rate. It is hoped that the reserve counting rate capacity in excess of the 2.6 drops per minute average would be sufficient to count random rapid sequences of drops. Further testing will be required to determine accurately the proper

## TABLE 1

FILTER PAPER MEASUREMENTS OF DROP SIZE

January - May, 1964

| RAINFALL RATE (Millimeters/hr.) | NUMBER OF DROPS/SQ. CM./MIN. | RANGE OF DROP SIZES (Millimeters) | TOTAL NUMBER OF DROPS |
|---|---|---|---|
| 0.0-0.5 | 1.69 | 0.7-2.5 | 1612 |
| 0.5-1.0 | 2.72 | 0.7-2.1 | 4275 |
| 1.0-1.5 | 3.62 | 0.7-3.1 | 3844 |
| 1.5-2.0 | 4.25 | 0.7-2.9 | 3237 |
| 2.0-3.0 | 4.96 | 0.7-3.3 | 4727 |
| 3.0-6.0 | 4.87 | 0.7-3.9 | 3008 |
| 6.0-12.0 | 6.24 | 0.7-4.5 | 942 |
| 12.0-24.0 | 11.10 | 0.7-3.7 | 359 |

average to maximum counting rate relationship.

Several additional drop-sizing runs have been made. Since these were made in the lee of a building exhibiting an aerodynamic wake and since they were made with developmental equipment, they are not to be scrutinized meticulously for their meteorological significance, but rather for the proof that they provide of the satisfactory operation of the drop-sizing instrumentation.

Figure 24 shows a comparison of six filter paper samples to 35 minutes of terminal velocity measurements made one hour earlier. The comparison is remarkable in that both records, even though they were made an hour apart, showed the majority of drops in the 0.5 to 1.3 millimeter range. Figures 25 (a), (b), and (c) exhibit the low threshold and the fine resolution of the electronic, terminal velocity technique.

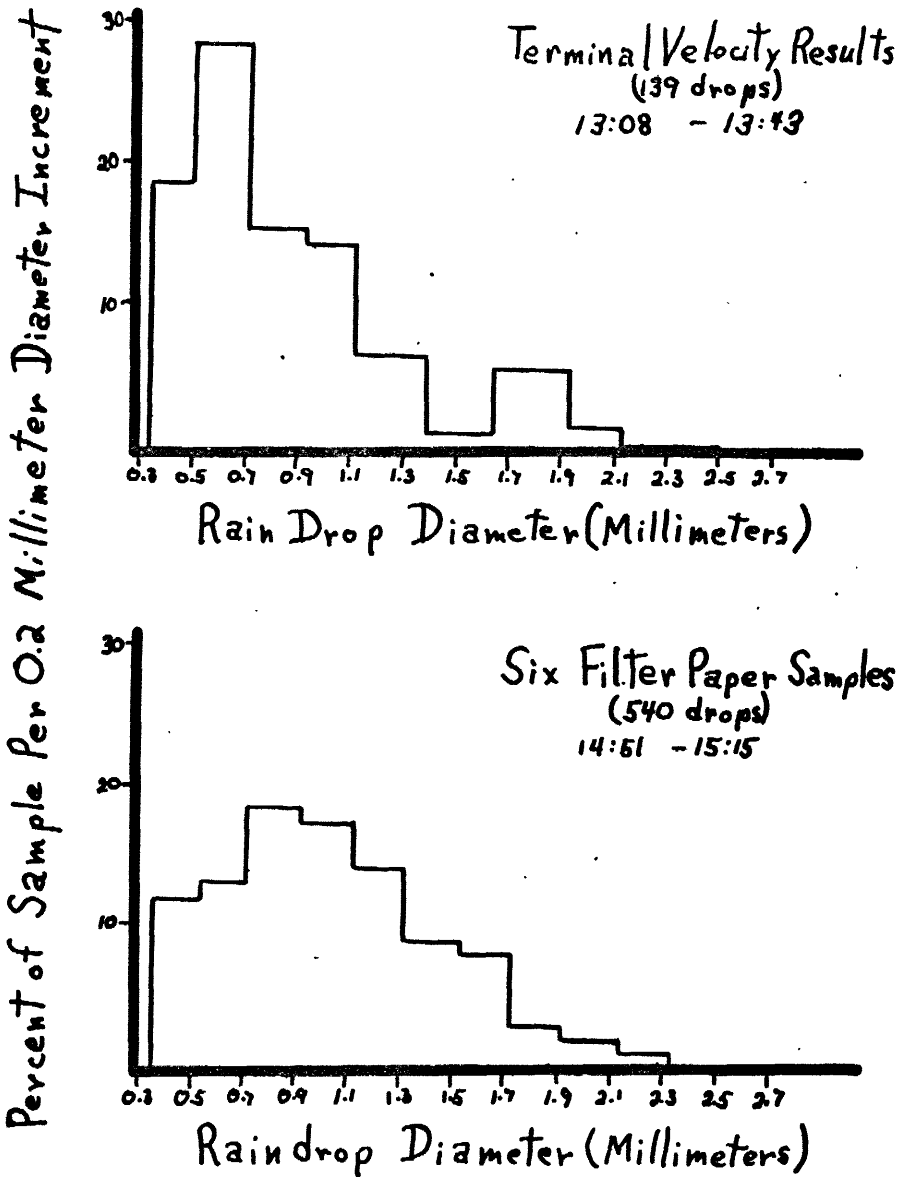
A test of the complete, automatic, recording, raindrop-sizing system was executed on February 25, 1965. The results exhibited similar characteristics to the average of filter paper measurements made during the middle of the storm (Figure 26), even though the results had to be distinguished from false results from radar interference and even though the sensitivity of the sensor had been made non-uniform from mechanical shock. In all measurements the majority of drop sizes fell in the 0.5 to 1.1 millimeter size range. Notable differences are that the filter paper measurements showed a much higher percentage of 0.7 millimeter drops, whereas the automatic technique indicated more uniform numbers of 0.5 to 1.1 millimeter drops. The problems experienced on February 25, 1965 with radar interference prohibited a point by point analysis of the differences between the terminal velocity and the filter paper techniques; but it is significant that the terminal velocity technique measured drops in the same size range as the filter paper technique.

Further comparisons between the terminal velocity and the filter paper techniques are to be conducted during the spring of 1965. These tests will be made with the six unit, surface sensor and with an automatic reset circuit. It is expected that detailed comparisons between the two techniques will be possible at that time.

Figure 24

A Comparison of Filter Paper and Terminal Velocity Techniques of Measuring Raindrop Sizes

December 4, 1964



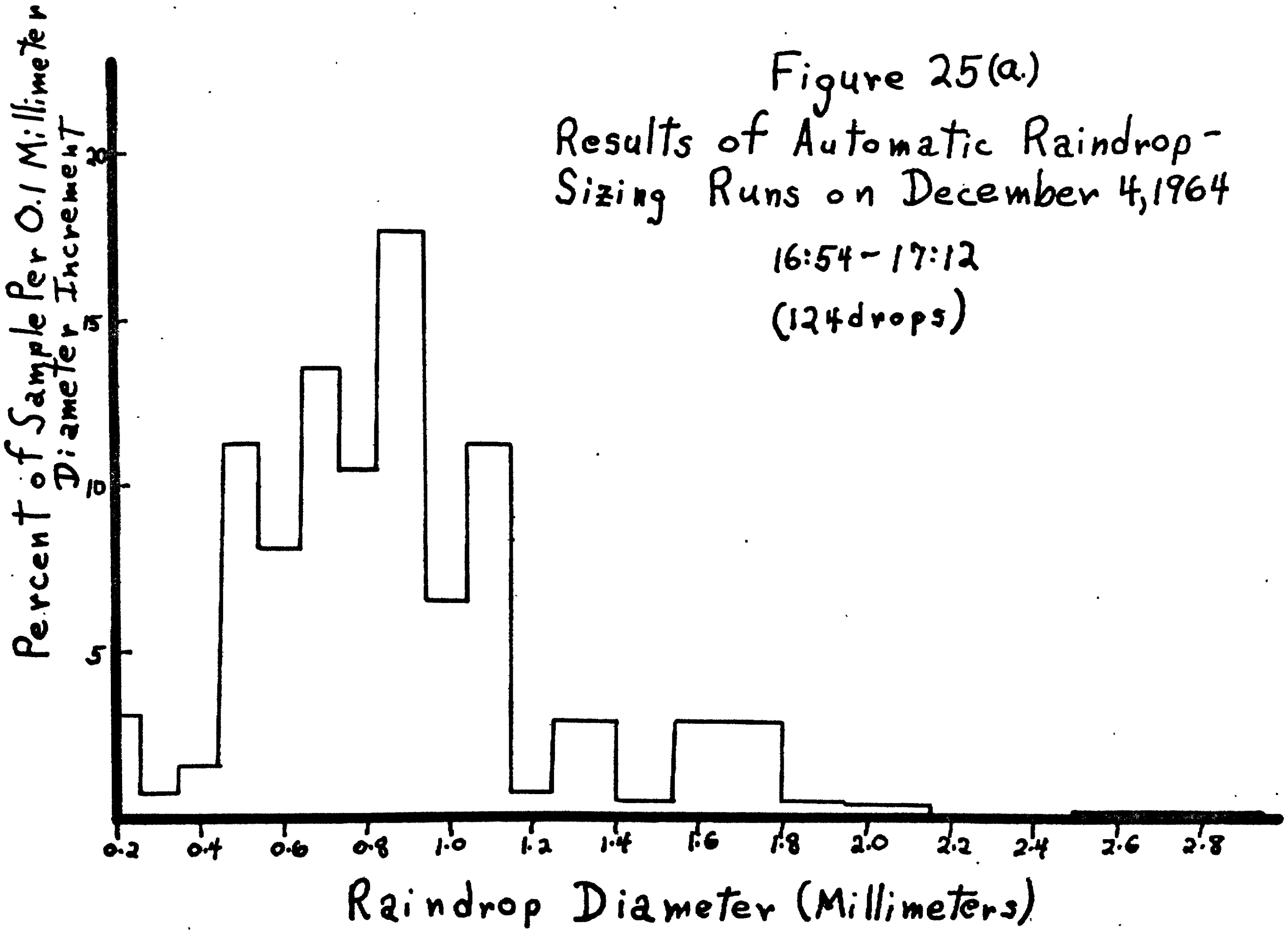



Figure 25(a.)
Results of Automatic Raindrop-Sizing Runs on December 4, 1964
16:54 - 17:12
(124 drops)

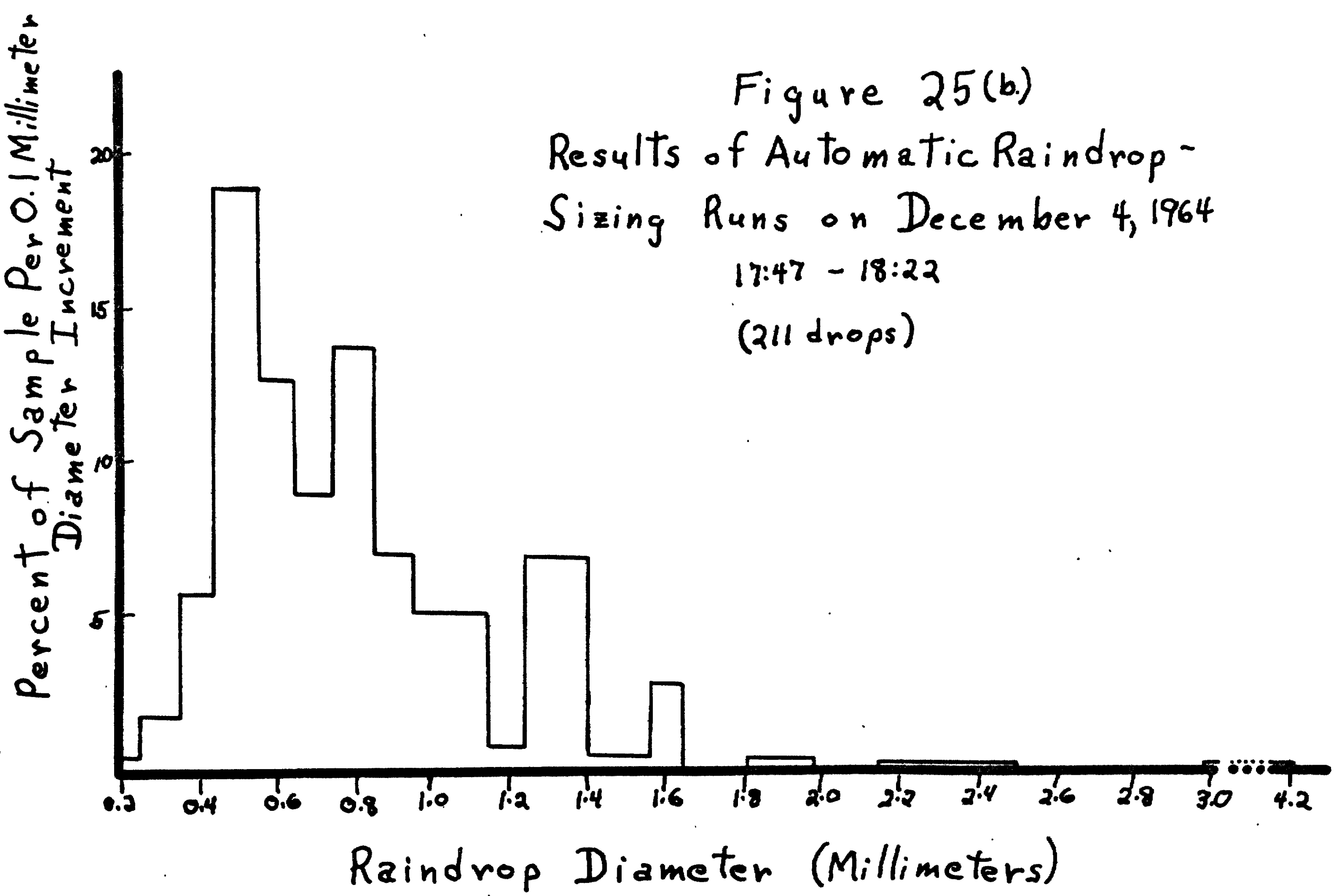



Figure 25(b.)
Results of Automatic Raindrop-Sizing Runs on December 4, 1964
17:47 - 18:22
(211 drops)

Figure 25(c)
Results of Automatic Raindrop-
Sizing Runs on December 4, 1964
19:35 - 20:06
(168 drops)

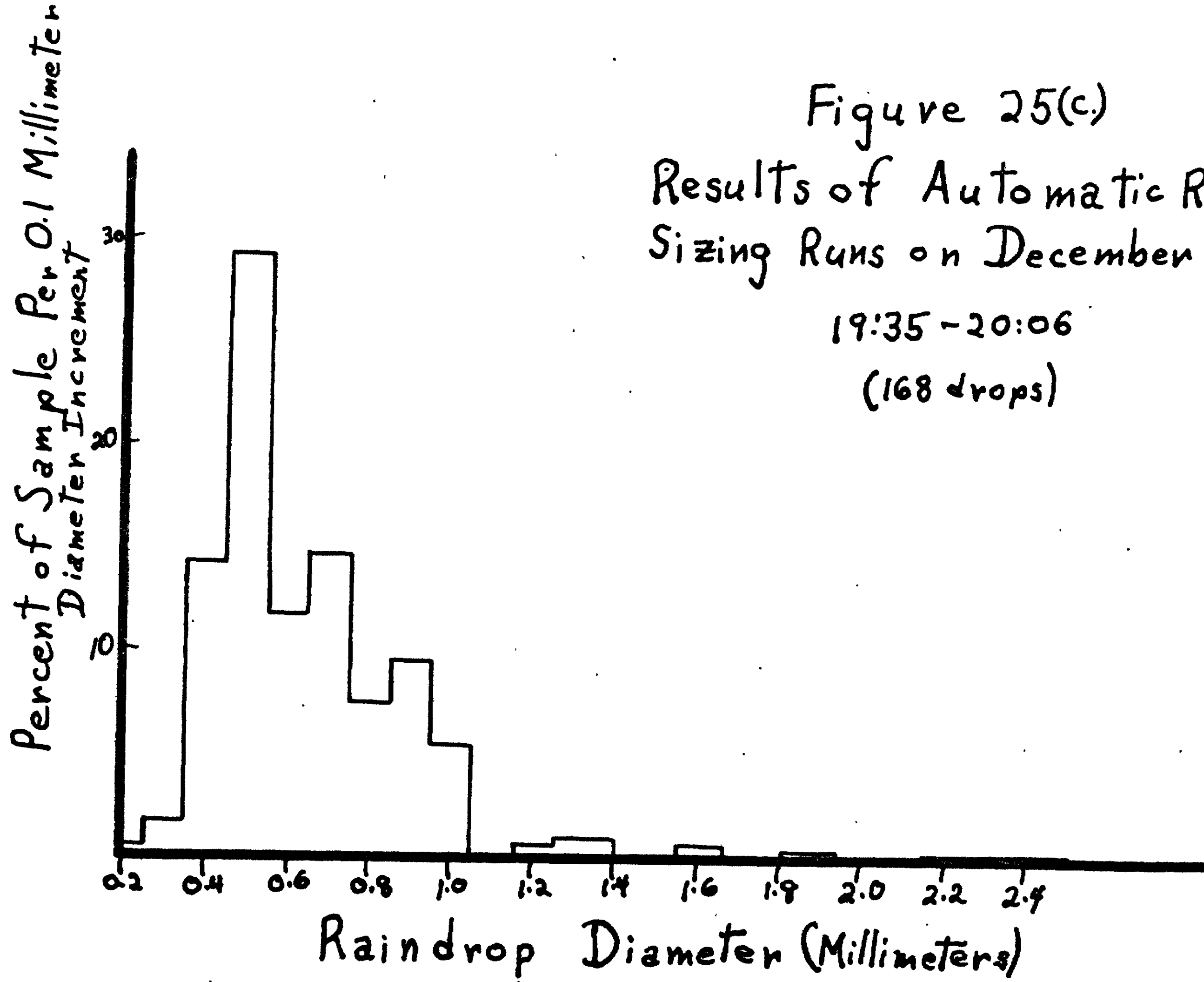
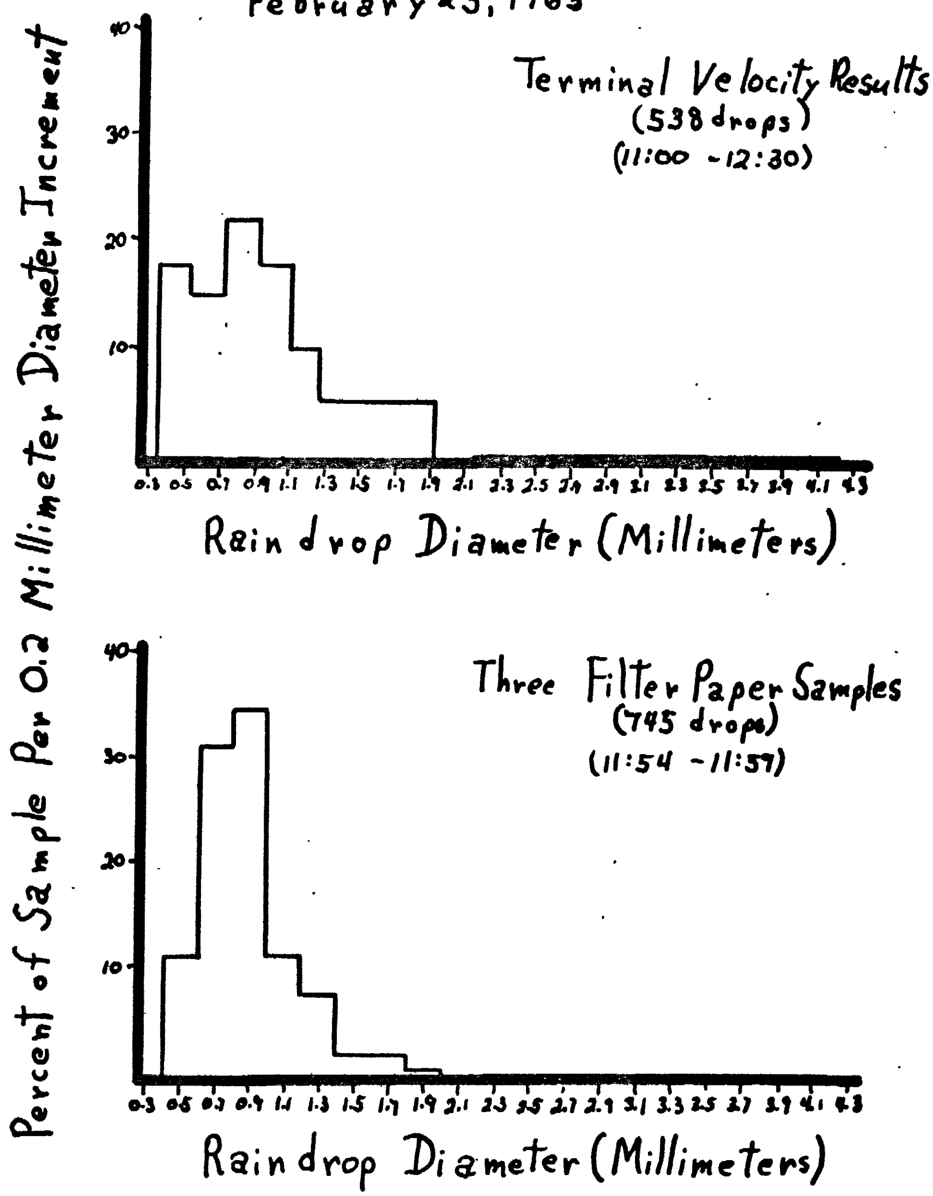


Figure 26

A Comparison of Filter Paper and Terminal Velocity Techniques of Measuring Raindrop Sizes, Using Automatic Equipment

February 25, 1965



## VI. DISCUSSION OF ERRORS

Errors in the measurement of drop-size distributions by the method of timing their fall velocities may arise in any of four different ways. First, there may be instrumental errors concerned with the measurement of velocity. Secondly, since the relationship between the terminal velocities of the drops and their diameters is the product of experiment, there may be errors involved with the assignment of drop diameters to drops with certain terminal velocities. Thirdly, there are meteorological problems which could produce incorrect interpretation of the measured velocities. Lastly, there may be sampling restrictions which could cause misleading raindrop-size distributions.

Instrumental errors in the measurement of velocity are possible from either inaccurate timing or from incorrect measurement of the vertical displacement of the two light beams. Since the counter yields five place accuracy in counting milliseconds and only three place accuracy is required to measure time to the hundredth of a millisecond, this means that there is less than a tenth of a percent inaccuracy in the timing of the passage of the drops. The spacing of the light beams has been measured to an accuracy of 98%. It is believed, therefore, that instrumental errors are less than 3% in the measurement of the vertical velocities of the drops.

One test of the accuracy of the instrument was a test of whether or not the system yielded reproduceable data. During the testing of the components of the system, water drops were constrained to pass through the sensor from a capillary siphon positioned directly above it. These drops were roughly 3.3 millimeters in diameter and they passed through the sensor at a rate of one per second. The time interval for the passage of these drops was always displayed on the oscilloscope as the same time to within visual resolution on the one millisecond per centimeter scale. This provided proof of the reproduceable nature of the measuring technique.

Inaccuracies in recording the drop sizes directly from the waveforms visible on the oscilloscope forced the total automation of the interval timing. The waveforms corresponding to the drop sizes most in need of distinction for weather radar purposes were crowded into one centimeter of a ten centimeter scale. Table 2 shows the transit times in milliseconds necessary to traverse a one centimeter gap for different drop sizes. The time intervals cover two decades and cannot be measured visually on a single oscilloscope time scale with high accuracy over their entire drop-size range.

The second possible source of errors in the measurement of drop-size distributions, that involving the terminal velocity, drop-size relationship, may be considered even less important than the instrumental errors. Several researchers have investigated this

TABLE 2

| RAINDROP DIAMETER (Millimeters) | SENSOR TRANSIT TIME (Milliseconds) |
|---|---|
| 0.2 | 10.1-11.5 |
| 0.3 | 8.1-10.0 |
| 0.4 | 5.8-8.0 |
| 0.5 | 4.1-5.7 |
| 0.6 | 3.6-4.0 |
| 0.7 | 3.2-3.5 |
| 0.8 | 2.9-3.1 |
| 0.9 | 2.6-2.8 |
| 1.0 | 2.4-2.5 |
| 1.1 | 2.2-2.3 |
| 1.2 | 2.1 |
| 1.3 | 2.0 |
| 1.5 | 1.9 |
| 1.6 | 1.8 |
| 1.7 | 1.7 |
| 1.9 | 1.6 |
| 2.0 | 1.5 |
| 2.3 | 1.4 |
| 2.7 | 1.3 |
| 3.2 | 1.2 |
| 5.2 | 1.1 |

relationship, and they all agree to within a few percent of each other. Since the relationship that was chosen by the author used the experimental results from three different investigations, it is estimated that the errors produced by this cause are not greater than 2%.

The meteorological source of errors is that which is concerned principally with turbulent, vertical, air motions in the vicinity of the sensor. At the ground the vertical velocity goes to zero, so it is expected that measurements made near the ground will be affected only slightly by such motions. However, consideration of vertical air motions will be of utmost concern in the interpretation of raindrop-size information taken in flight.

The final source of errors concerns the representativeness of the sample. A non-representative sample can be taken in each of three ways. First, if the drop-size distribution is changing very rapidly, such as at the beginning of a thunderstorm, the sampling rate of five drops per second may not be adequate to obtain a sufficient sample before the drop-size distribution changes. The option of recording the output of the instrument directly on tape and processing it by a computer will allow a maximum drop-counting rate of approximately 100 per second. Secondly, there is an instrumental problem which arises if either the light intensity is non-uniform across the widths of the light beams or if the photoresistor responses are not uniform across their diameters. The net result of either of these conditions is a non-uniform sensitivity across the widths of the light beams which will produce raindrop-size distributions with fewer of the small drops than the number that actually existed. This source of errors was found to be present in the equipment immediately after the automatic data run on February 25, 1965; therefore, it is presumed that that data may have contained the effects of such a non-uniformity, probably caused by a mechanical shock. The third problem is not one of incorrect sampling, but one of insufficient sampling. Slanting rain, as described in Section III, will not produce incorrect results, but certain of the drops which intercept the upper light beam will not intercept the lower one. A record of the number of such drops will exist in the form of characteristically large and uniform measurements. It will then be possible to compute the percent of the sample that has been missed and to correct the deficiency if the total sample size warrants it.

## VII. COORDINATION OF DROP-SIZE, RAINGAUGE, AND WEATHER RADAR MEASUREMENTS

It is desirable to coordinate all three types of measurements by making raingauge and drop-size measurements at a close network of stations directly beneath the volume of air sampled quantitatively by the radar. As yet, insufficient drop samples have been taken by the terminal velocity technique, and the drop samples that have been taken by the filter paper technique were not taken under the volume of air sampled by the radar.

Although a number of drop-size data have been collected by the filter paper technique and Z-R relationships computed using Z from the expression $Z = \sum D^6$, where D is the diameter of the drops, and R from a sum of the volumes of the water drops arriving at the ground within a given time; no comparisons had been made between $Z_e$, the equivalent Z measured by the radar and $R_r$, the rainfall rate as measured by raingauges.

However, quantitative radar and rainfall rate data for the same volume of air have been made at M.I.T. during the past six years. The author has performed a study of 38 measurement periods during 36 storms to evaluate the relationship between $Z_e$ and $R_r$. The data consisted of simultaneous radar reflectivity and recording raingauge records. The raingauge measurements were made on the surface at a point 17.3 miles distant from the radar while the radar was set to measure the reflectivity of the volume directly over the raingauge. Unfortunately, the sampled volumes of the two types of measurements.varied greatly even though that volume sampled by the raingauge was always included in that sampled by the radar (approximately $10^8$ meters$^3$). Since the radar was always measuring an average rainfall rate, the raingauge read higher or lower depending upon whether or not the rainfall rate that it was measuring was above or below the radar average. Also the two measurements may have differed if there were any droplet growth or evaporation in the lowest few thousand feet of the atmosphere. The amount that each of these two conditions affected the comparison has not been determined.

The comparison was made by first shifting the records slightly in time to achieve agreement, then selecting corresponding values of both $\underline{\log Z_e}$ and $\underline{R_r}$ at one minute intervals, and finally by graphing these values in order to determine their relationship. Figure 27 (a) is an example of one such plot in which the estimated line of best fit is $Z = 200R_r^{1.6}$ with only a small scattering of points around the line. Figure 27 (b) shows that the estimated line of best fit can correspond to that assumed from drop-size measurements even though there is a wide scattering of points. Figures 27 (c) and (d) illustrate the fact that in many storms the relationship between $\underline{Z_e}$ and $\underline{R_r}$ is not the normally assumed $Z_e = 200R_r^{1.6}$.

Table 3 summarizes the graphs through a tabulation of the parameters described in Figures 27 (a), (b), (c), and (d).

Figure 27 (a)
Radar - Raingauge Comparison

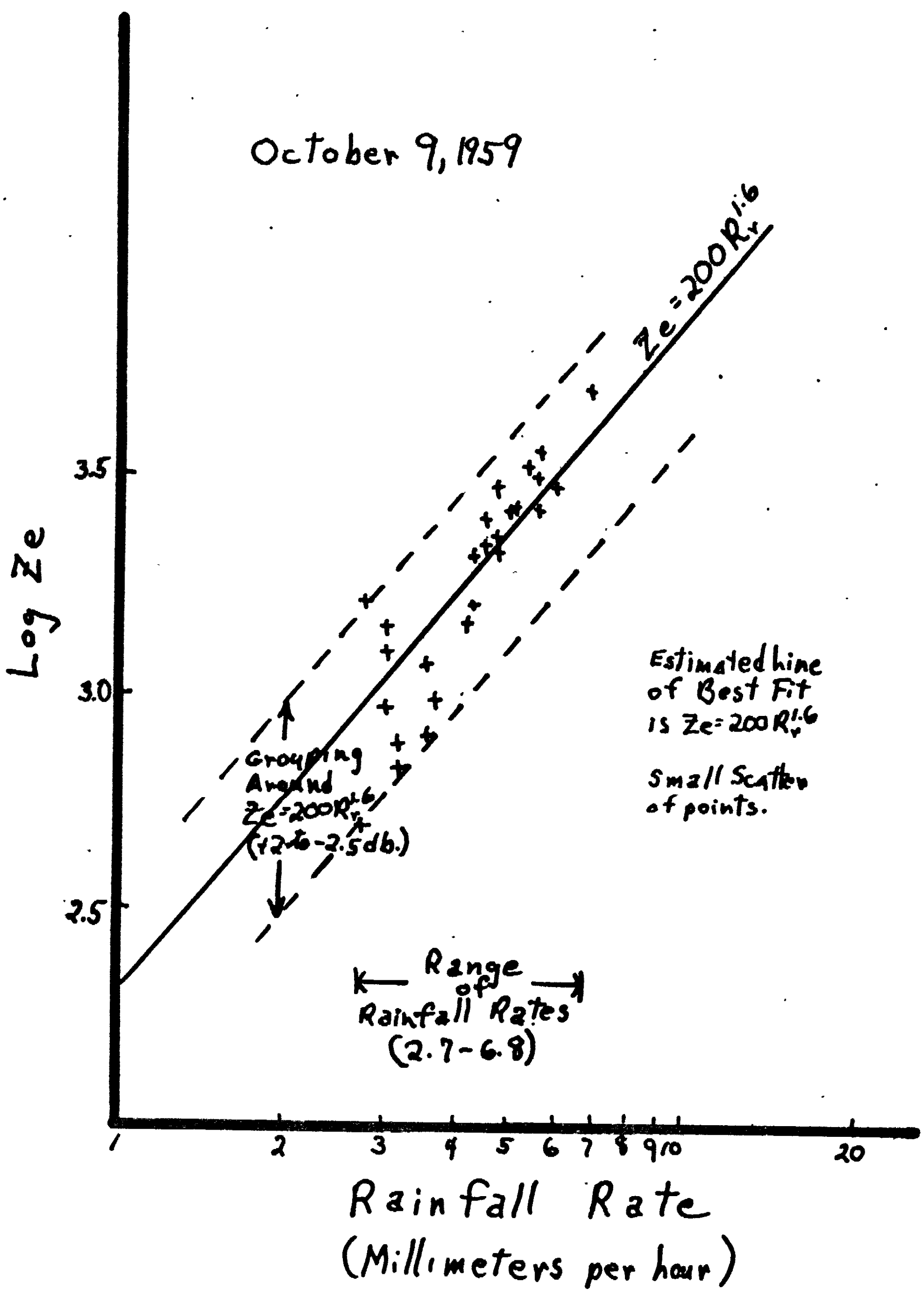


Figure 27 (b)
Radar - Raingauge Comparison

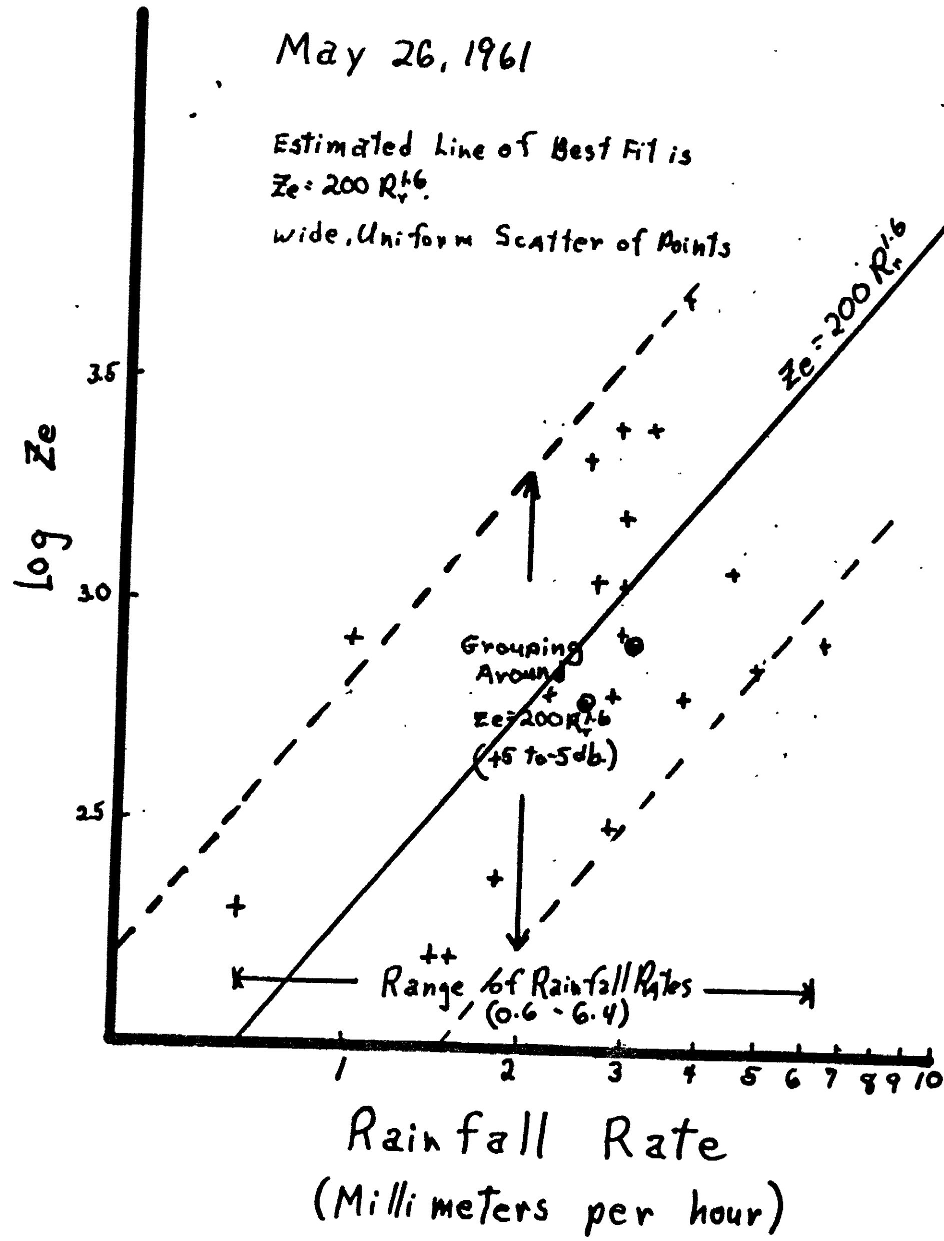


Figure 27 (c.)

Radar - Raingauge Comparison

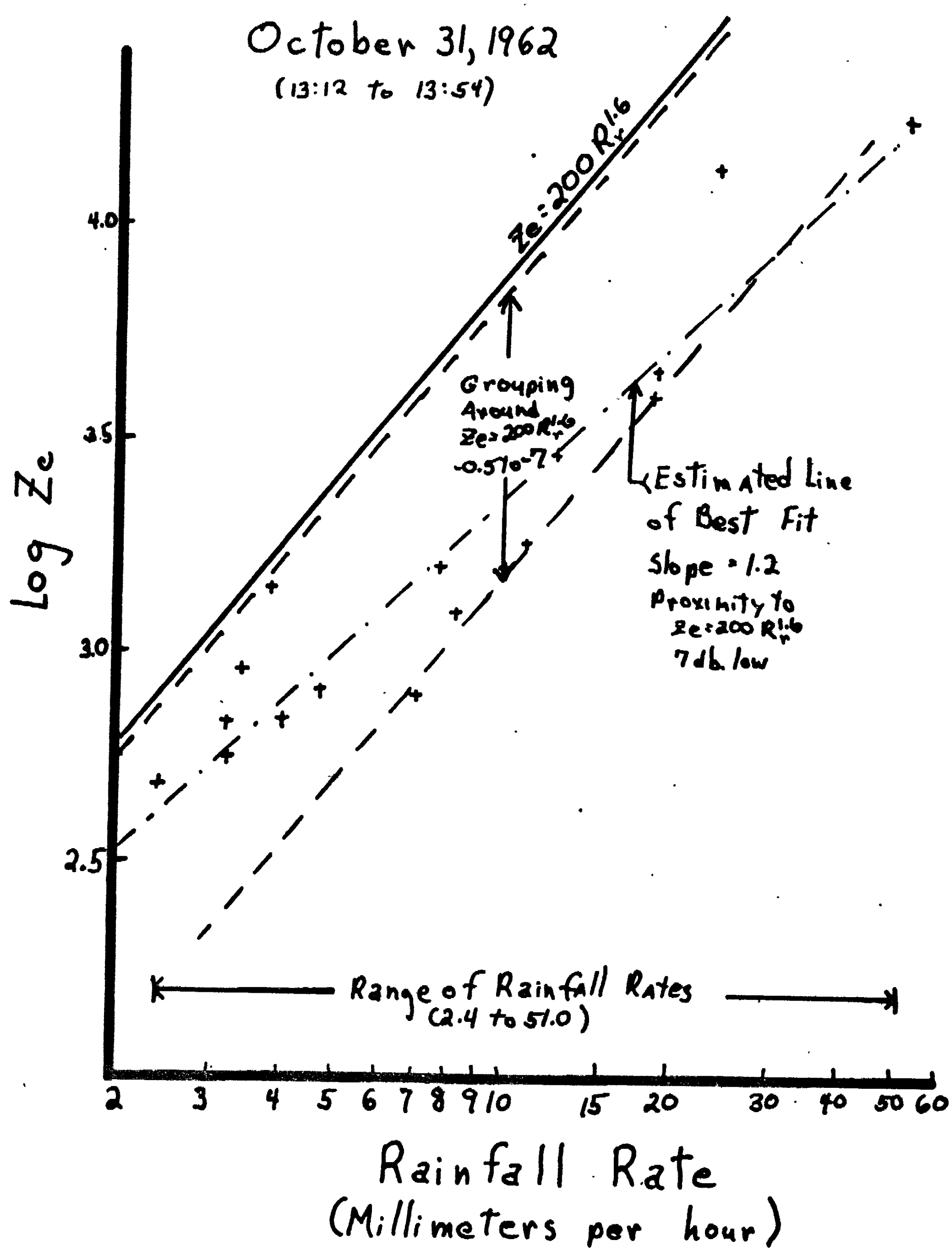
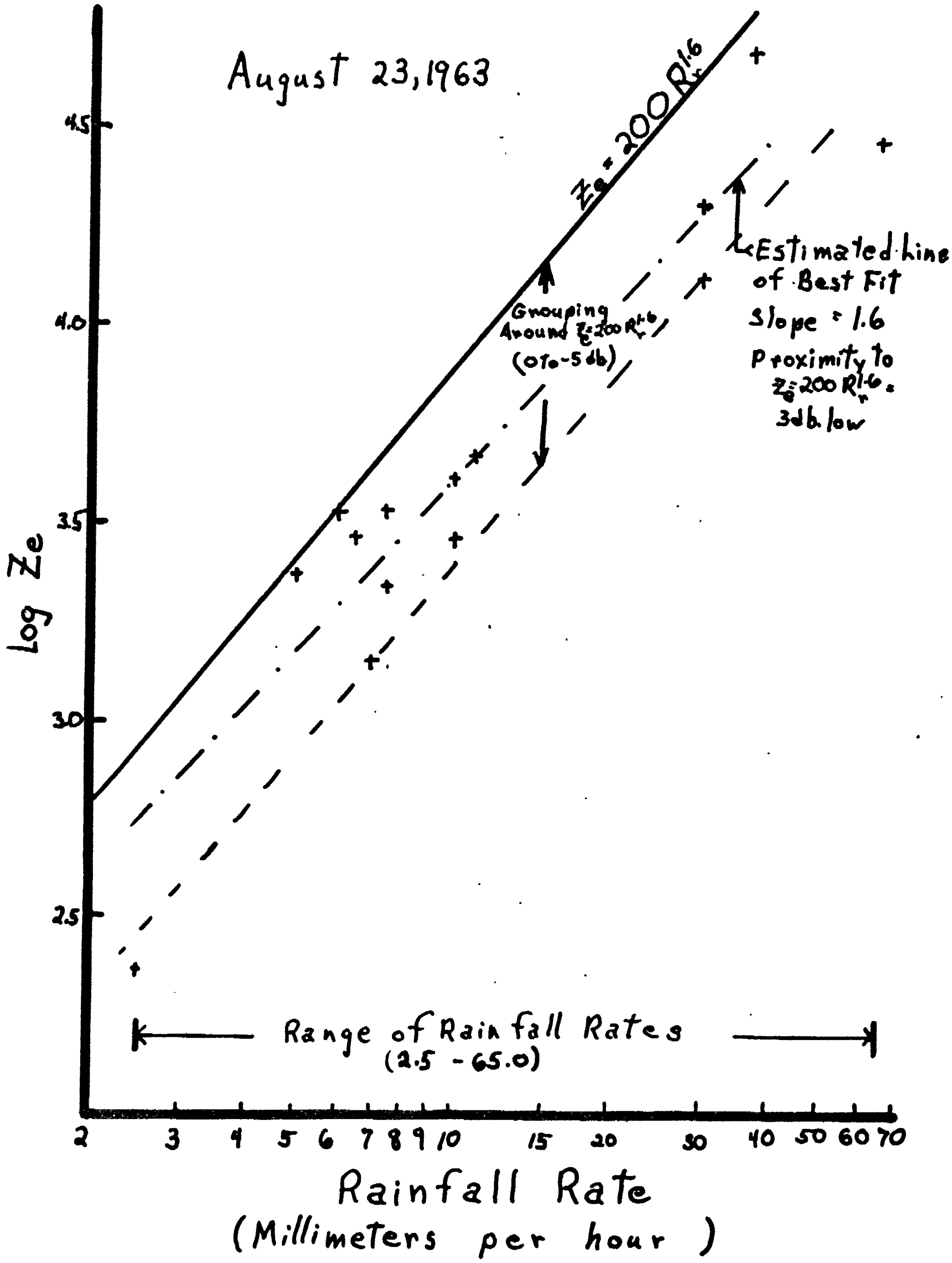


Figure 27 (d.)
Radar - Raingauge Comparison



## TABLE 3

## COMPARISON OF INDEPENDENTLY MEASURED RAINFALL RATES AND RADAR REFLECTIVITIES

| DATE | RANGE OF RAINFALL RATES (db.) | GROUPING AROUND $Z = 200\ R^{1.6}$ (db.) |
|---|---|---|
| Oct. 9, 1959 | 2.7 - 6.8 | 2 to -2.5 |
| Nov. 17, 1959 | 1.0 - 5.4 | 0 to -6 |
| Nov. 25, 1959 | 0.2 - 2.9 | 4 to 0 |
| Dec. 12, 1959 | 1.6 - 6.3 | 2 to -2 |
| Jan. 3, 1960 | 0.9 -.2.2 | 3 to -4.8 |
| Jan. 15, 1960 | 1.5 - 5.6 | 2 to -4 |
| May 9, 1960 | 1.2 - 8.7 | 0 to -5 |
| May 11, 1960 | 0.6 - 2.5 | 3 to -1.5 |
| | 2.5 - 26.0 | 0 to -5 |
| June 4, 1960 | 0.8 - 5.4 | 2 to -5 |
| July 30, 1960 | 0.7 - 5.0 | 0 to -8 |
| May 12, 1961 | 1.2 - 2.9 | -5 to -7 |
| May 16, 1961 | 3.0 - 5.9 | 3 to -2 |
| May 26, 1961 | 0.6 - 6.4 | 5 to -5 |
| July 31, 1961 | 2.5 - 75.0 | 4 to -6 Most Points |
| | 7.0 - 75.0 | 0 to -9.5 |
| Sept. 15, 1961 | 1.0 - 3.6 | 3 to -3 |
| Nov. 14, 1961 | 1.0 - 4.6 | 5 to -1 |
| March 12, 1962 | 1.2 - 5.0 | 6 to -4.5 |

TABLE 3

| DATE | RANGE OF RAINFALL RATES (db.) | GROUPING AROUND $Z = 200 R^{1.6}$ (db.) | |
|---|---|---|---|
| June 12, 1962 | 5.4 - 13.0 | 0 to -4 | Most points |
| Oct. 5, 1962 (1340 - 1434) | 1.2 - 4.9 | 2 to -4.6 | |
| (1607 - 1634) | 2.3 - 8.4 | -4 to -8.5 | |
| Oct. 6, 1962 | 1.7 - 2.7 | 1 to -9 | |
| Oct. 10, 1962 | 0.3 - 2.7 | 3.5 to -3.5 | |
| Oct. 31, 1962 (1312 - 1354) | 2.4 - 51.0 | -0.5 to -7 | |
| (1442 - 1453) | 1.3 - 4.2 | 1 to -6 | |
| Nov. 3, 1962 | 1.2 - 29.0 | 0 to -8 | Most points |
| Jan. 11, 1963 | 2.0 - 6.3 | 6 to -3<br>3 to -3 | <br>Most points |
| March 13, 1963 | 0.8 - 1.8 | 6 to 0 | |
| July 8, 1963 | 5.3 - 83.0 | -3.5 to -22.5 | |
| Aug. 23, 1963 | 2.5 - 65.0 | 0 to -5 | |
| Sept. 29, 1963 | 1.5 - 11.0 | 0 to -14 | |
| Nov. 7, 1963 | 2.3 - 3.3 | -1 to -3.5 | |
| Nov. 29, 1963 | 1.3 - 14.0 | -2 to -4 | |
| Jan. 21, 1964 | 1.1 - 4.4 | 5.5 to 0 | |
| Jan. 25, 1964 | 0.1 - 28.0 | 14 to -12 | |
| March 25, 1964 | 0.4 - 4.9 | 3 to -8 | |
| Aug. 5, 1964 | 5.0 - 44.0 | -7 to -14 | |
| Aug. 18, 1964 | 3.6 - 32.0 | 0 to -12 | Most points |
| Aug. 31, 1964 | 1.0 - 17.5 | 0 to -8.5 | |

TABLE 3

| DATE | ESTIMATED LINE OF BEST FIT SLOPE | / PROXIMITY TO $Z = 200 R^{1.6}$ | REMARKS |
|---|---|---|---|
| Oct 9,1959 | 1.6 | Superimposed | Good fit |
| Nov. 17, 1959 | 2.0 | 2 db. low | 12 db. scatter |
| Nov. 25, 1959 | 1.6 | - | - |
| Dec. 12, 1959 | 1.6 | 1 db. low | Only seven reliable points |
| Jan. 3, 1960 | ? | Indeterminate | 0.3-0.6 mm./hr. values of Z questionable |
| Jan 15, 1960 | 1.6 | 4 db. low | 1.5-4.5 mm./hr. |
| | 1.6 | 2 db. high | 4.5-5.6 mm./hr. |
| May 9, 1960 | 1.9 | Av. 3 db. low | - |
| May 11, 1960 | 0.9 | 2 db. high | 0.6-2.5 mm./hr. |
| | 0.9 | 3.5 db. low | 2.5-26.o mm./hr. |
| June 4, 1960 | 1.6 | 2 db. low | Only 6 points (5 good) |
| July 30, 1960 | 3.3 | 6 db. low | Wide scatter |
| May 12, 1961 | 1.6 | 6 db. low | Small scatter |
| May 16, 1961 | 1.6 | 0.5 db. high | Excluded are points for R greater than 5.9 mm./hr. because they are -16.5 db. from the line. |
| May 26, 1961 | 1.6 | Superimposed | Wide, uniform scatter |
| July 31, 1961 | 1.6 | Av. 1 db. low | Cluster of rainfall rates (3-14.5 mm./hr.) for log Z between 3.4 and 3.66. |
| Sept. 15, 1961 | 2.4 | Good | Very good grouping |

TABLE 3

| DATE | ESTIMATED LINE OF BEST FIT SLOPE | PROXIMITY TO $Z = 200 R^{1.6}$ | REMARKS |
|---|---|---|---|
| Nov. 14, 1961 | 1.6 | 1.5 db. high | - |
| March 12, 1962 | ? | Indeterminate | Wide scatter |
| June 12, 1962 | 2.0 | Av. 3 db. low | - |
| Oct. 5, 1962 (1340-1434) | 0.6 | Variable | Unusually small change in Z for a given change in R. |
| (1607-1634) | 2.2 | Av. 6 db. low | Good grouping |
| Oct. 6, 1962 | 1.6 | 7 db. low | Very low |
| Oct. 10, 1962 | 1.6 Av.<br>0.9 Init.<br>3.5 Final | One line 3 db. high, one line 3 db. low. Av. good | Data ignored for R less than 1 mm./hr. |
| Oct. 31, 1962 (1312-1354) | 1.2 | 7 db. low | Good line |
| (1442-1453) | 2.1 | 2.5 db. low | - |
| Nov. 3, 1962 | 1.0 | Indeterminate | Some points to -15 db. |
| Jan. 11, 1963 | ? | Indeterminate | Good grouping |
| March 13, 1963 | 2.7 | Variable | Good grouping |
| July 8, 1963 | ? | 10 db. low | Extreme spread of points |
| Aug. 23, 1963 | 1.6 | 3 db. low | Very little scatter about a line 3 db. low. |
| Sept. 29, 1963 | ? | 10 db. low | Wide scatter |
| Nov. 7, 1963 | ? | Indeterminate | Uniform rainfall rate prohibited estimate of slope. |

TABLE 3

| DATE | ESTIMATED LINE OF BEST FIT SLOPE | PROXIMITY TO $Z = 200 R^{1.6}$ | REMARKS |
|---|---|---|---|
| Nov. 29, 1963 | 1.6 | 2.5 db. low | Only six points |
| Jan. 21, 1964 | 1.6 | 3 db. high | Good grouping |
| Jan. 25, 1964 | 1.6* | 10 db. high* | Extremely wide scatter * Some suggestion of a line 10 db. high. |
| March 25, 1964 | 0.5 | Variable | - |
| Aug. 5, 1964 | 1.1 | 9 db. low | - |
| Aug. 18, 1964 | 1.6 | 10 db. low | - |
| Aug. 31, 1964 | 1.2 | 5 db. low | Suggests modes of precipitation. Uniform slope of 1.2 throughout, even though line shifts 4 db. down for 13 minutes in the middle of the storm and then shifts back. |

## SUMMARY OF THE GRAPHICAL ANALYSIS

The average spread of points is 7.5 db.

The average estimated line of best fit is 3.4 db. low. (Using 27 identifiable lines)

The average slope of the lines is 1.5.

Of 32 lines exhibiting discernable slopes, 16 were considered to be 1.6.

Seasonal Averages (Numbers of cases appear in parentheses.)

| Season | Average Position of Est. Best Fit Line (Db. above or below $Z_e = 200 R_r^{1.6}$) | Average Slope | Average Spread of Points (db.) |
|---|---|---|---|
| Spring | -1.8 (6) | 1.6 (6) | 7.1 (7) |
| Summer | -5.2 (10) | 1.8 (8) | 9.0 (9) |
| Fall | -4.2 (8) | 1.6 (13) | 6.3 (15) |
| Winter | 2.0 (5) | 1.6 (4) | 6.4 (5) |

The above tabulation may be interpreted by saying that the high occurrence of very small, but very active, convective cells in the summer causes the reflectivities for given rainfall rates to be 5.2 db. low, on the average. Also, it is evident that an increase in the average spread of points occurs in the summer season. It is interesting to note that the average slope remains very nearly constant, while the individual slopes range from 0.9 to 3.5. One final observation is that, on the average, winter storms form distributions 2.0 db. above the line $Z_e = 200 R_r^{1.6}$. This means that the average reflectivity is 2 db. above what was expected for a given rainfall rate.

This study gives us an idea of how the average $Z_e$-$R_r$ relationship varies with season. However, there are still many variations in individual cases which will require the use of drop-size instruments to be investigated fully. In this way, we may obtain the rainfall rates directly from the individual raindrops and eliminate the additional problems connected with raingauges.

These radar-raingauge observations, in themselves, provide enough proof of a seasonal variation in the $Z_e$-$R_r$ relationship to justify further study of this variation by means of drop-size instrumentation.

## VIII. CONCLUSIONS

A raindrop-sizing instrument for both surface and airborne measurements has been designed, and experimental models have been constructed. Also an improved version of the surface model has been designed and built which overcomes the sampling limitations of the experimental models.

It has been shown that the measurement of raindrop sizes through the measurement of their terminal velocities is both feasible and practical. The advantages of this type of measurement are of three types. First, the technique provides for continuous measurement, thus allowing for the changes in distributions of raindrop sizes during all stages of various storm types. Secondly, the method requires a comparatively short processing time which may be shortened further by channelling the output of the device directly to a magnetic tape recorder for ultra-rapid computer processing. Thirdly, the basic technique employed for determining the sizes of the drops is an improvement over other continuous techniques because it is an "on-off" timing process and does not depend on some quantitative property of the drop.

Tests of the airborne model have not been made. Questions concerning the uniformity of the balloon vehicle ascent rate and possible "umbrella" effects of the balloon will need to be assessed. Additional time will be necessary to permit the development of the conceived instrumentation into a telemetering, raindrop-sizing device which will transmit data instantaneously back to the recording station from an ascending, balloon platform. The principle problem which must be solved is that of increasing the sample area of the airborne instrument without drastically changing its size, weight, or flight characteristics.

An ideal platform for this telemetering, raindrop-sizing instrumentation would be a small blimp. If the sensor were mounted atop the blimp with the transmitter and power supplies suspended beneath the blimp, most of the problems of the meteorological balloon vehicle would be eliminated. A blimp would provide a comparatively stable platform for such measurements and could remain indefinitely at any height in the storm to collect sufficient drop samples. Also the blimp would be able to lift a comparatively heavy sensor with a sufficient sample area and lower it back to the surface without endangering the lives or properties of those persons beneath it.

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